Superconducting resonant cavities design and material development for quantum computing and quantum sensing applications

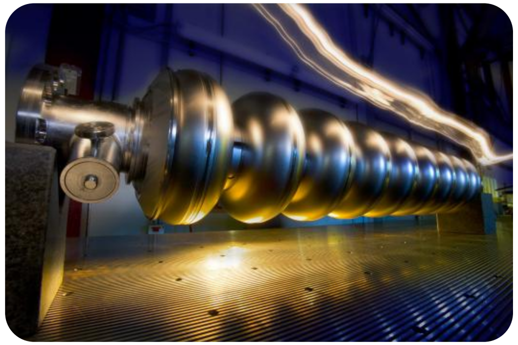
Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

DiSC

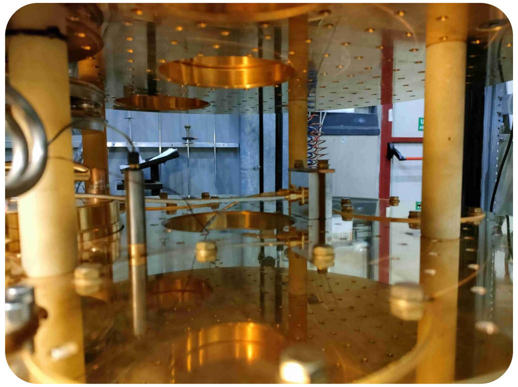
INTRODUCTION

Superconducting Resonant Cavities



Most common application is particle accelerators

Important parameters:
Cavity Quality factor (Q_0)
Accelerating field
Meissner regime
2 K or 4.2 K operation temperature



Quantum computing and sensing

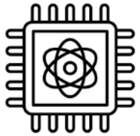
Important parameters:
Both Meissner and Shubnikov regime
mK operation regime
Cavity Quality factor (Q_0)

$$Q_0 = \frac{G}{R_s}$$

G — Depends on shape and frequency

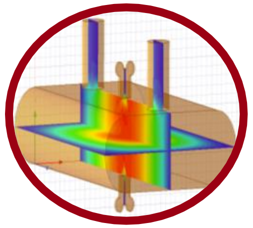
R_s — Depends on material/surface treatments

Outline



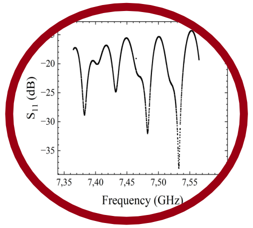
Quantum computing

Aluminum cavities for 3D transmon architecture



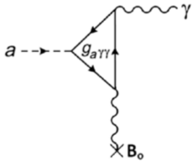
Design of a 7.46 GHz cavity

Fabrication using
pure Al vs Al alloy



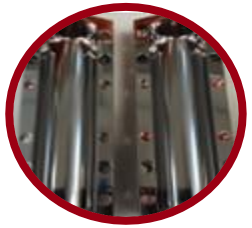
Characterization of the
Cavity + Qubit

Axion search



NbTi thin film on Cu cavities as haloscopes

Material selection & Characterization



Fabrication

Characterization at 4 K

Outline

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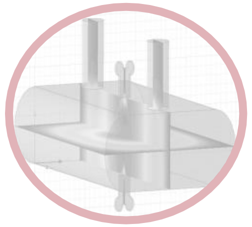

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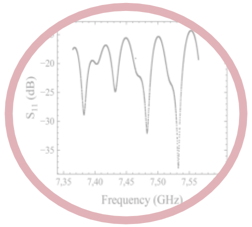

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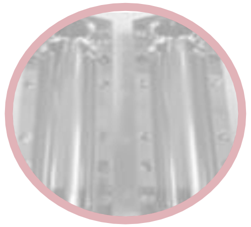


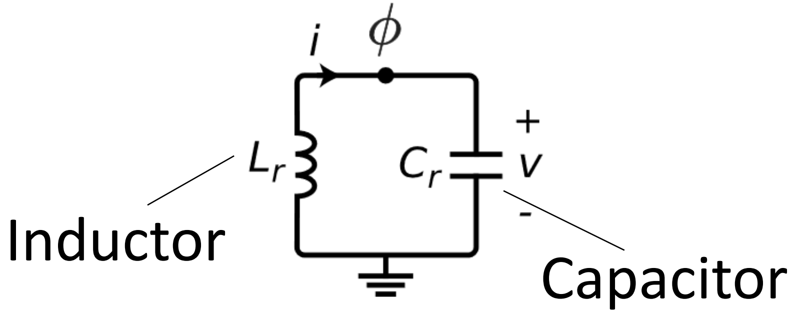
Fabrication

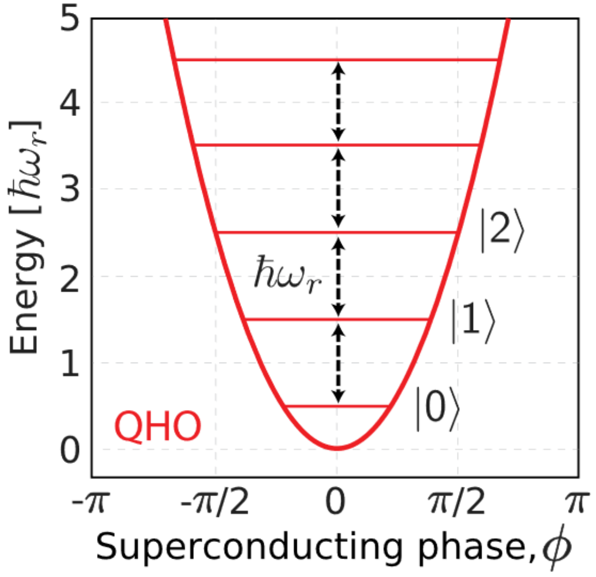
Characterization at 4 K

QUANTUM COMPUTING

INFN
UNIVERSITÀ DEGLI STUDI DI PADOVA

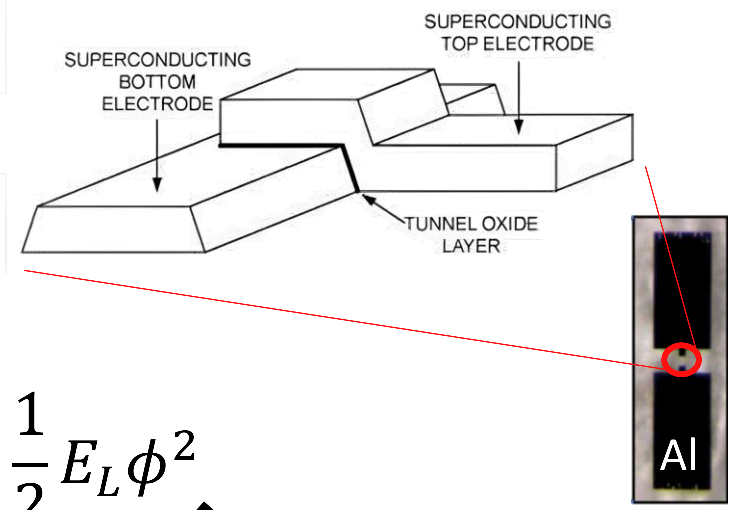
Harmonic resonator





$$H = 4E_C n^2 + \frac{1}{2} E_L \phi^2$$

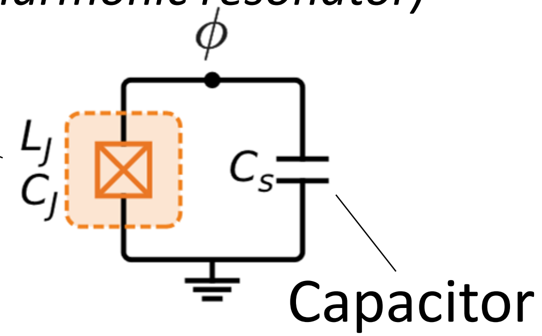
Josephson junction

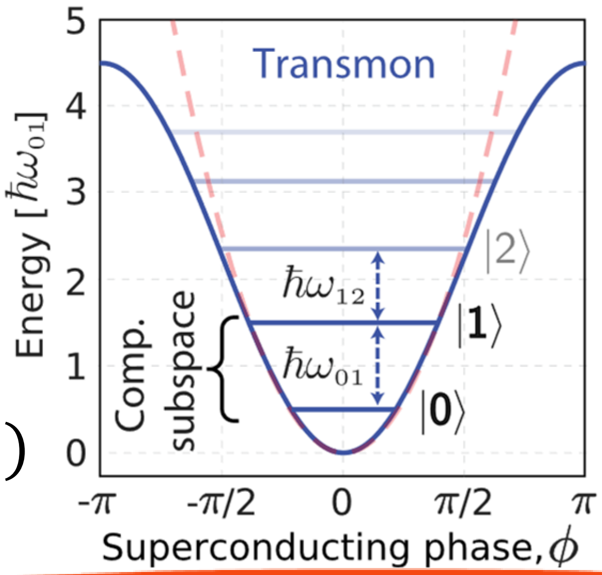


$$H = 4E_C n^2 - E_j \cos(\phi)$$

Transmon qubit

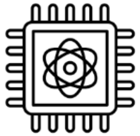
(Anharmonic resonator)





P. Krantz, et al., *Applied Physics Reviews*, vol. 6, fasc. 2, giu. 2019

OUTLINE



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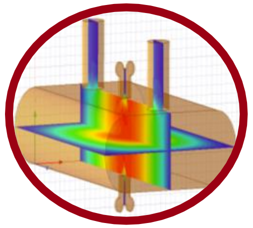

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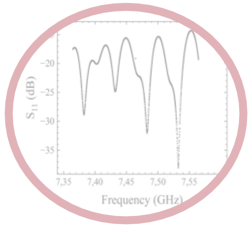

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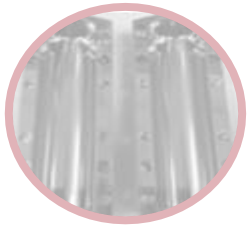
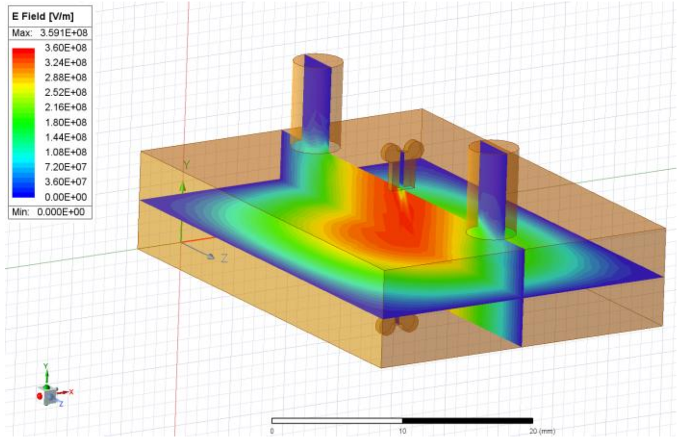
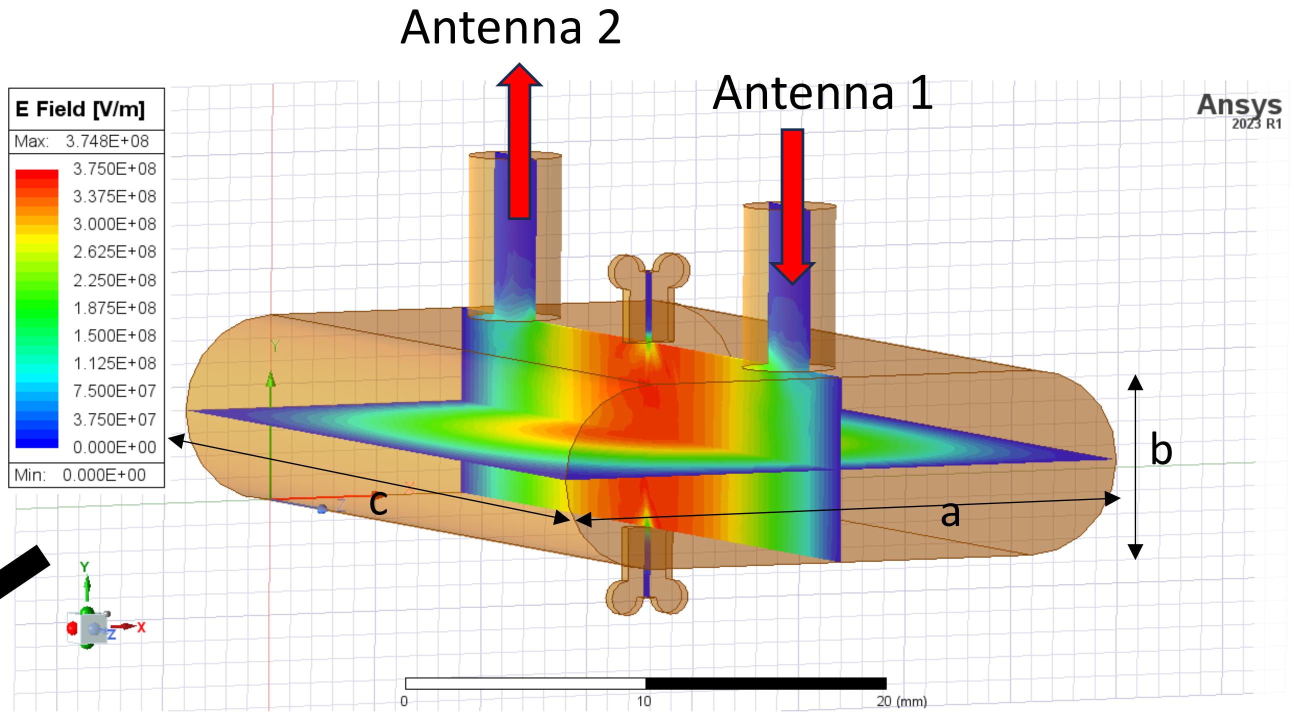


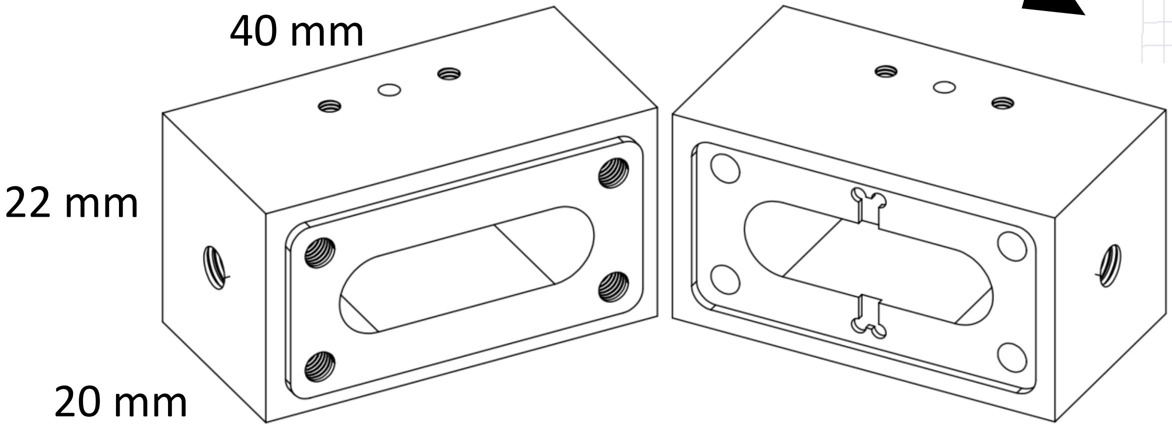
Fabrication

Characterization at 4 K

Shape optimization







Width	$a = 26\ mm$
Height	$b = 8\ mm$
Length	$c = 36\ mm$
Resonant frequency	$\omega_0 = 7.46\ GHz$

$\sim 1\ GHz$ detuning from qubit at $\simeq 6.50\ GHz$

Surface resistance estimation

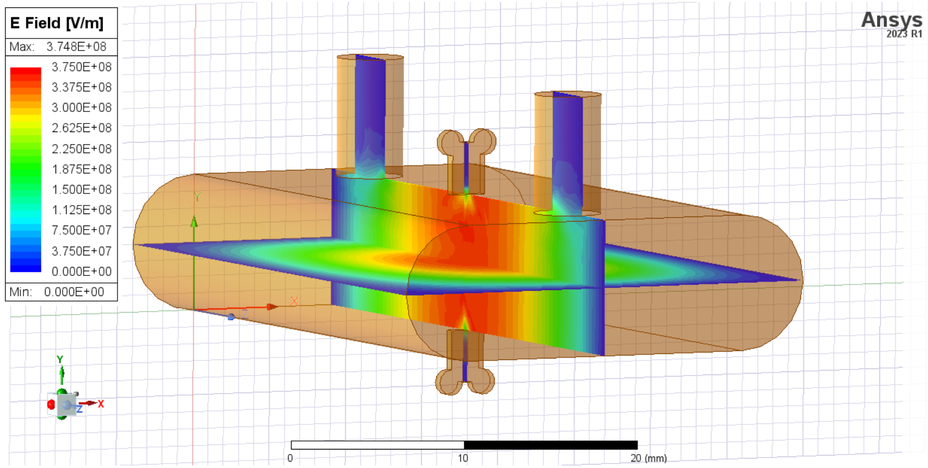
$$G = \frac{\omega_0 \mu_0 \int_V |\bar{H}|^2 dv}{\int_S |H|^2 ds} = 157.30\ \Omega$$

⬇

Using experimental value of Q_0
for the aluminum alloy cavity

⬇

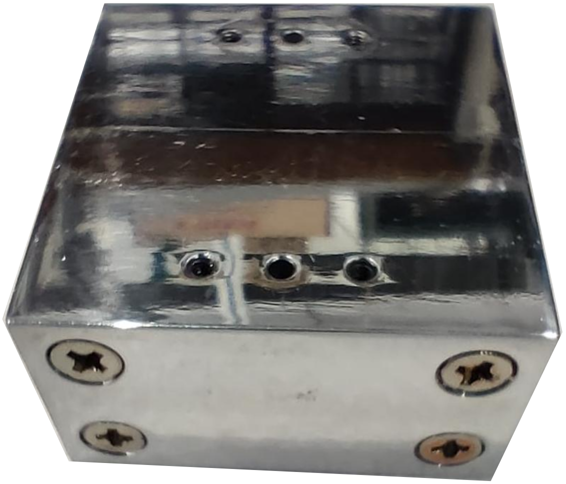
$$R_s = \frac{G}{Q_0} = (730 \pm 40)\ \mu\Omega \quad \Rightarrow \quad R_s = \cancel{R_{BCS}} + R_{res}$$



Cavity Simulation

Source	Q_0
Eigenmode simulation	$(2.16 \pm 1.2) \cdot 10^5$
Experimental	$(2.17 \pm 1.1) \cdot 10^5$

Simulation can reproduce experimental values



Alloy cavity and qubit fabricated at TII (Arab Emirates)

Al alloy

↓

Move to Al 5N (99.999% purity)

OUTLINE

Quantum computing

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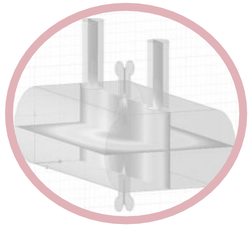

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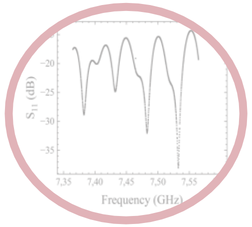

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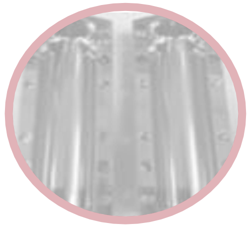
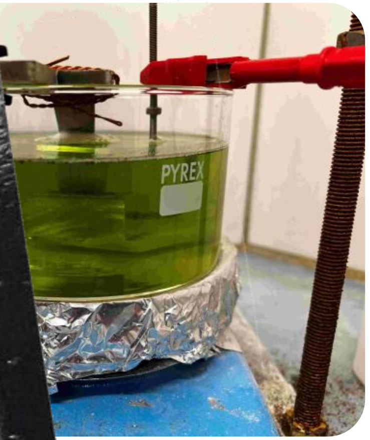


Fabrication

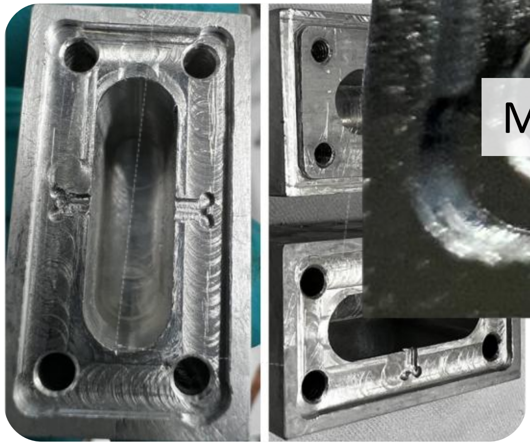
Characterization at 4 K

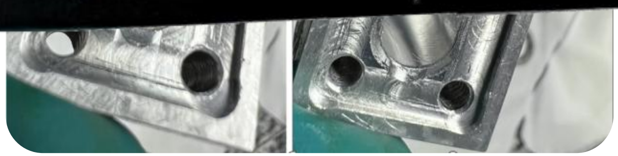
Cavity Fabrication

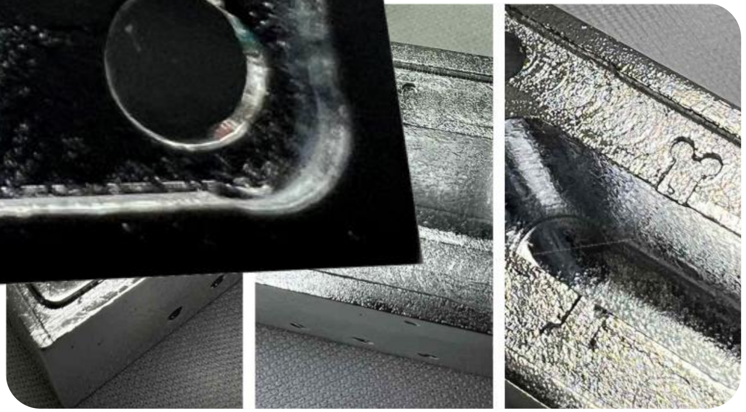


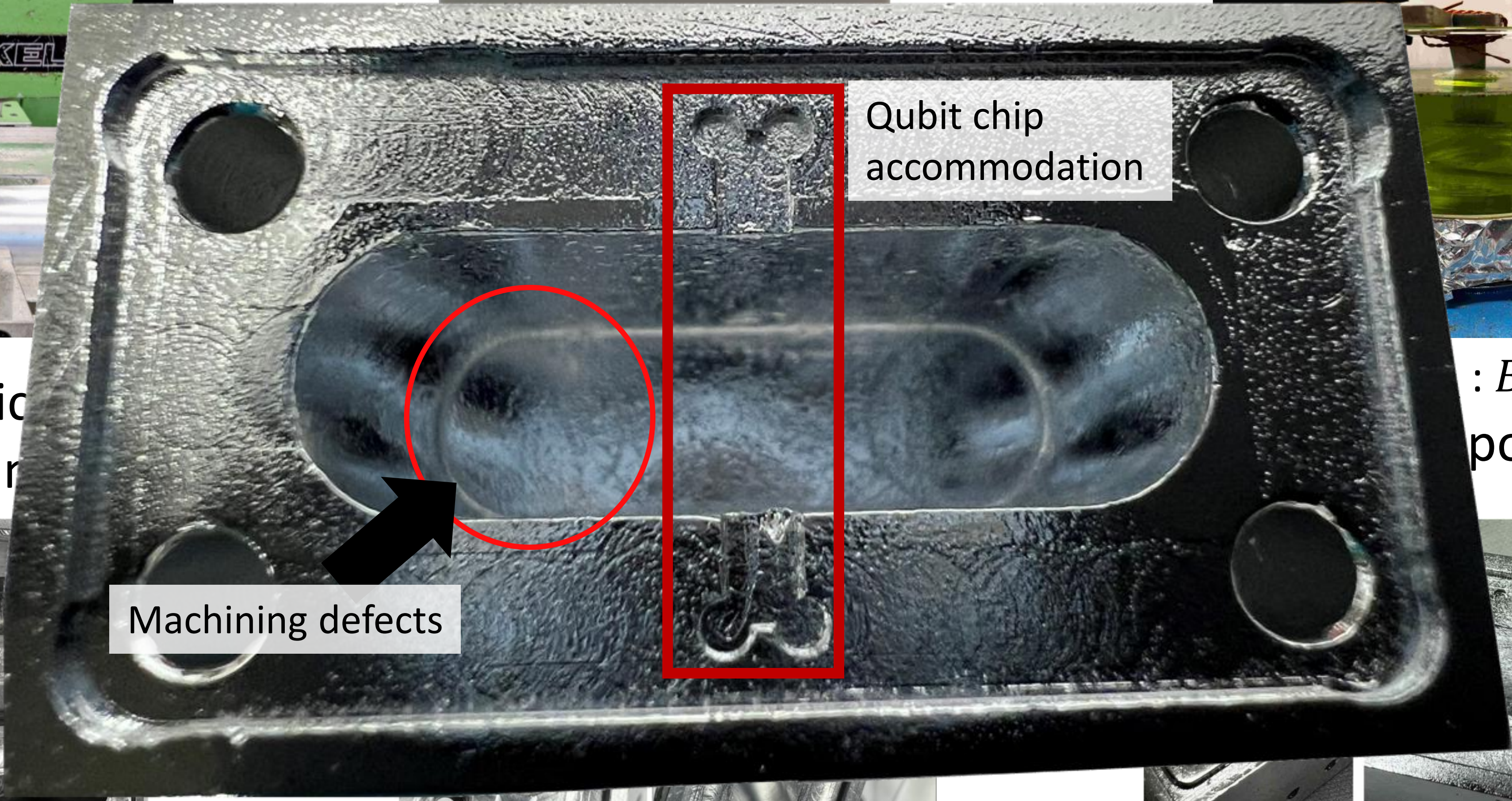
- Mechanic
  Machinin

: $BuAc$
polishing









OUTLINE

Quantum computing

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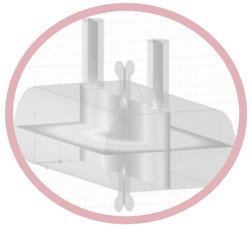

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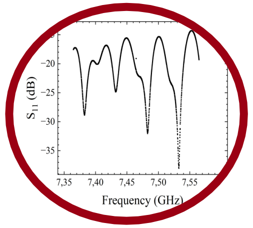

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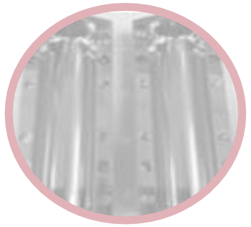


Fabrication

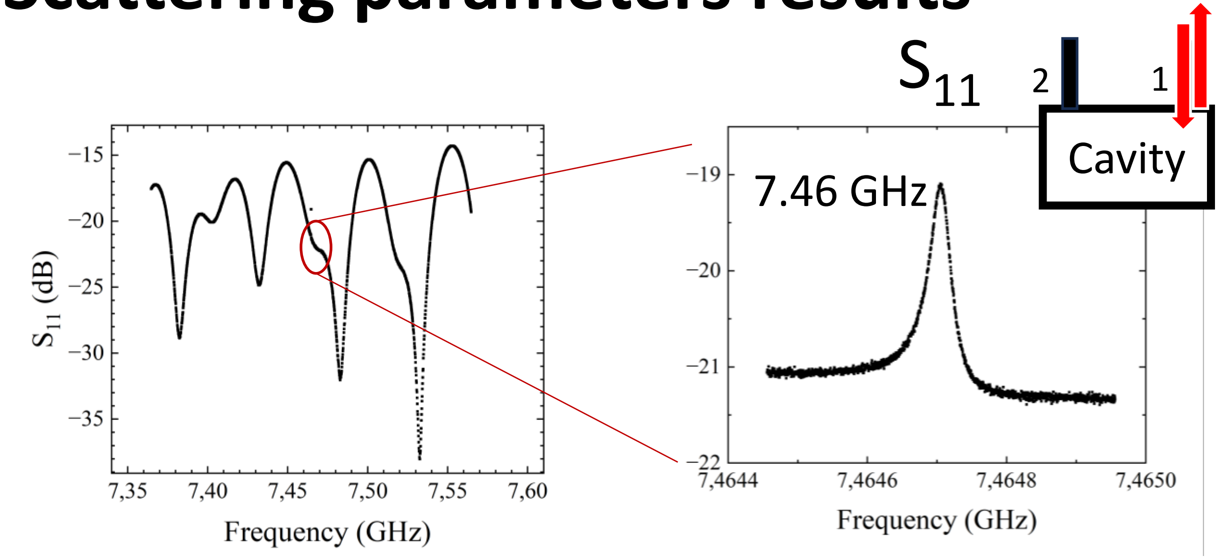
Characterization at 4 K

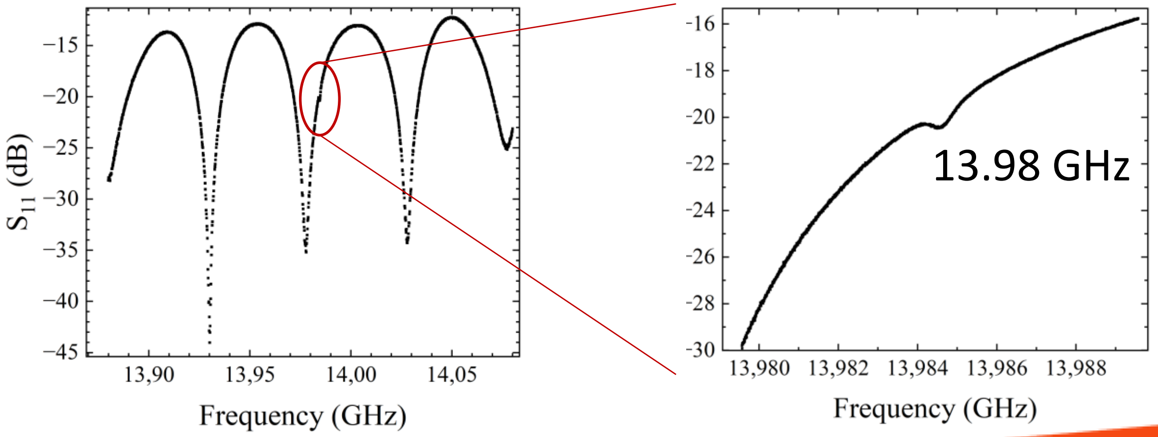
CAVITY CHARACTERIZATION

Measurements on pure Al cavity

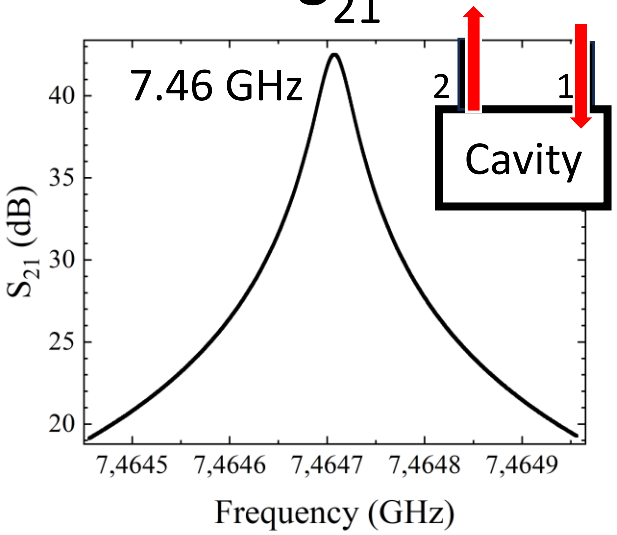
Scattering parameters results

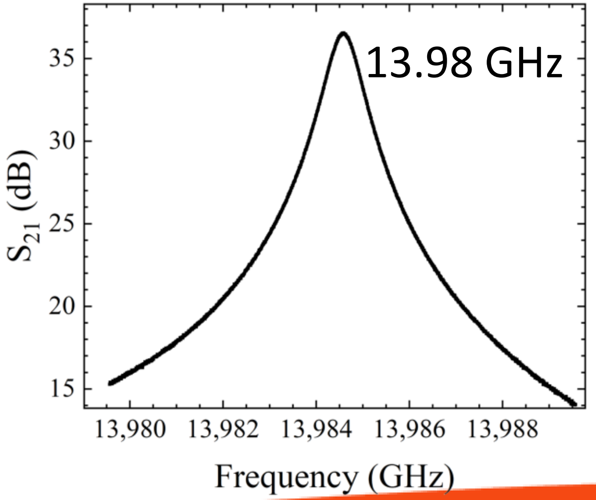
S_{11}

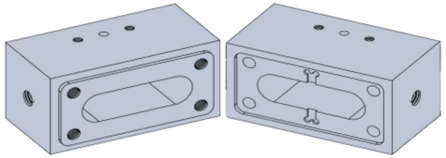




S_{21}







All measures at 30 mK

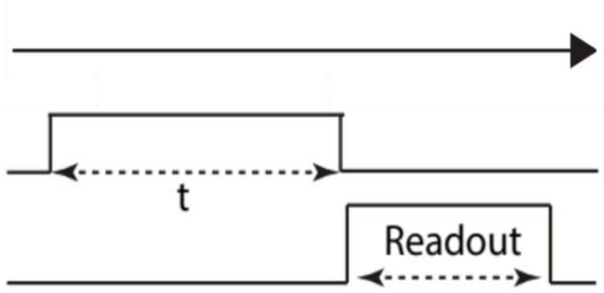
$\boldsymbol{Q_L = (2.2 \pm 1.0) \cdot 10^5}$

Already better than Al alloy cavity!

$Q_L = (1.78 \pm 0.9) \cdot 10^4$

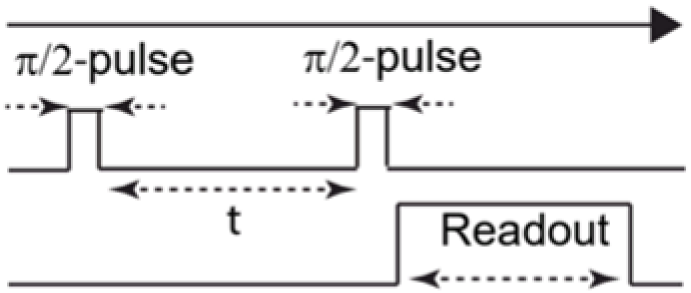
QUBIT CHARACTERIZATION

Rabi spectroscopy



$$p \propto \cos^2\left(\pi\tilde{\Omega}_R t + \phi\right)e^{-\frac{t}{T_1}}$$

Ramsey spectroscopy



$$p \propto \frac{1}{2} - \sin\left(2\pi k t + \phi\right)e^{-\frac{t}{T_2}}$$

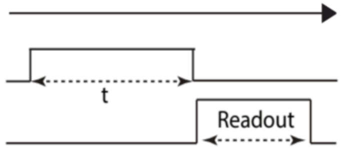
$$\tilde{\Omega}_R = \sqrt{\Omega^2 + \Delta^2}$$

detuning

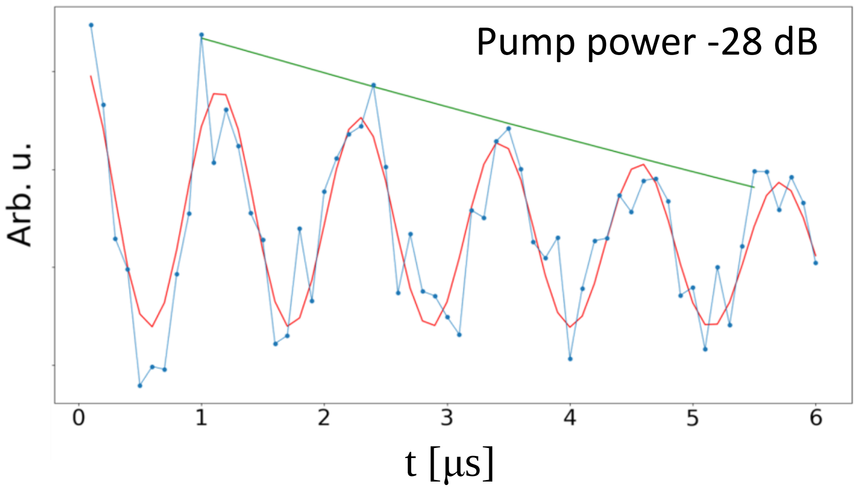
$$\Omega = \frac{d \cdot E}{\hbar}$$

of the drive

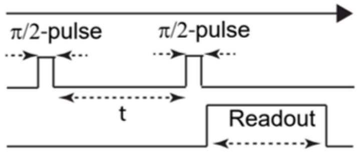
Transition dipole moment -> $\langle 1|\hat{d}|0\rangle$



Rabi spectroscopy



$$T_1 = (6.1 \pm 0.3)\mu s$$



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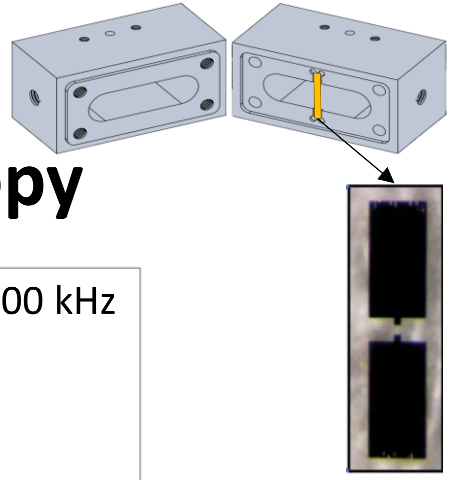
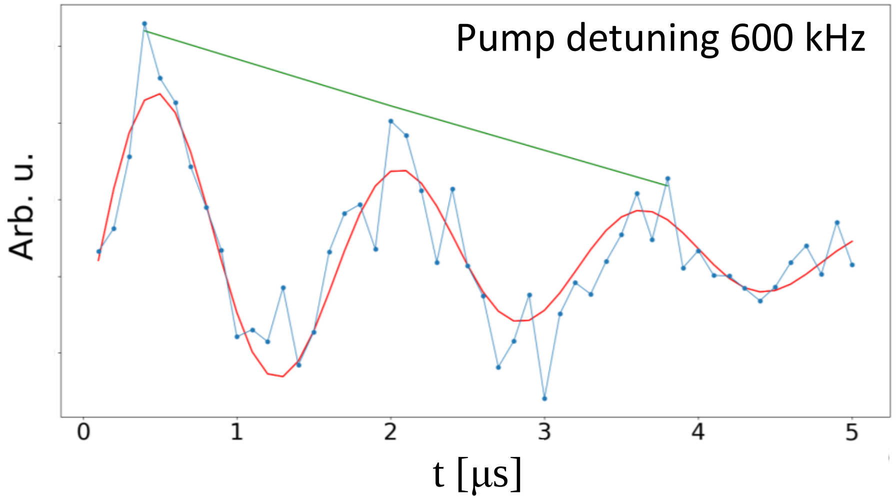
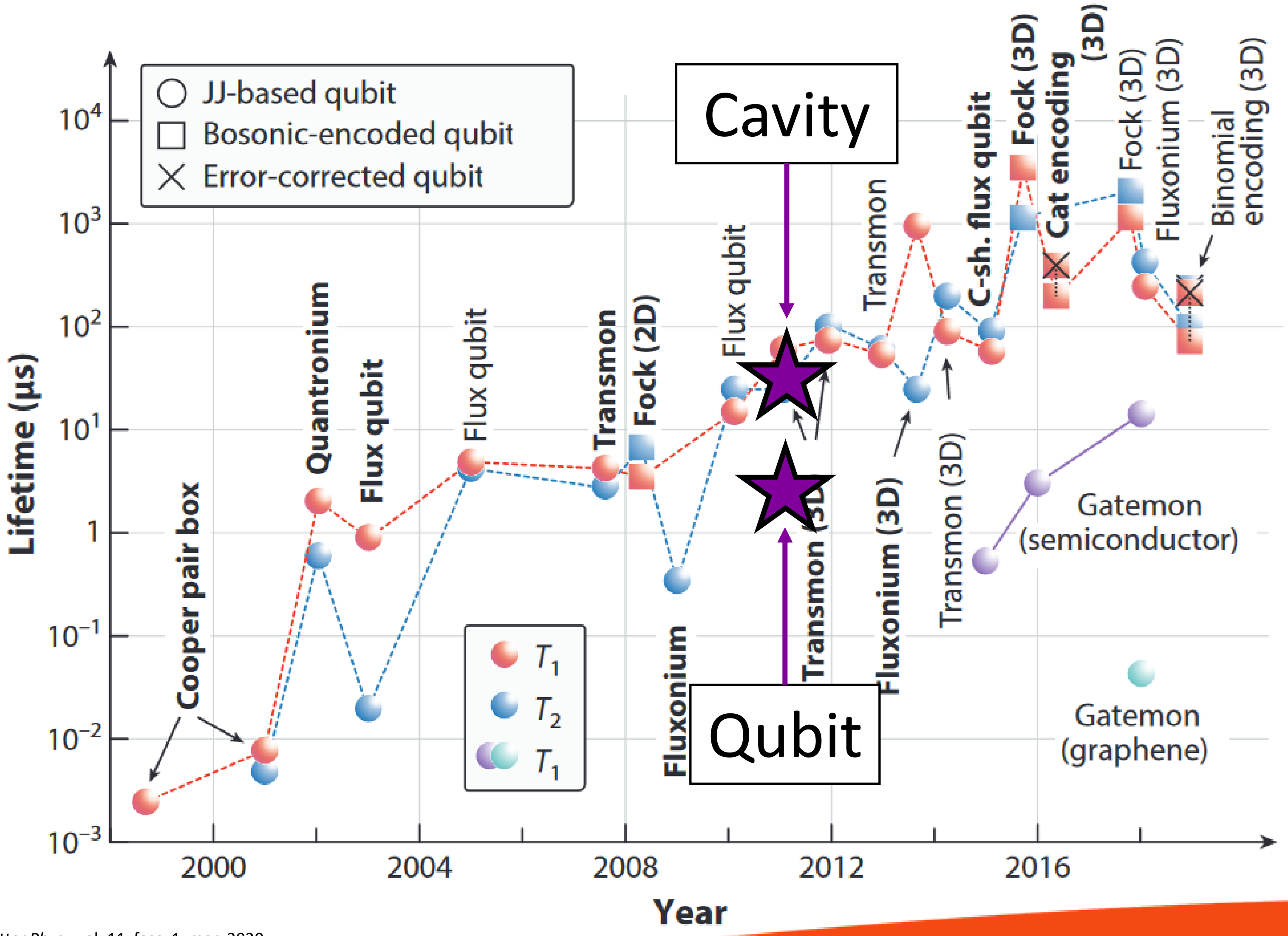




$$T_2 = (2.3 \pm 0.3)\mu s$$

Cavity characteristic time $\tau = \frac{Q_0}{\omega} \simeq 29\ \mu s$

Qubit Characterization



M. Kjaergaard *et al.*, *Annu. Rev. Condens. Matter Phys.*, vol. 11, fasc. 1, mar. 2020

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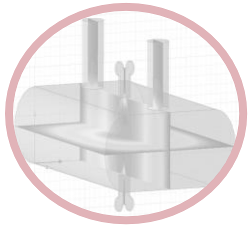

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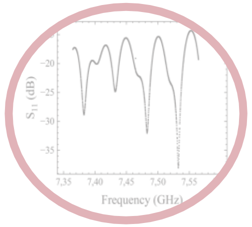

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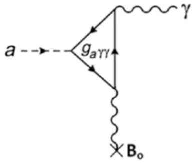

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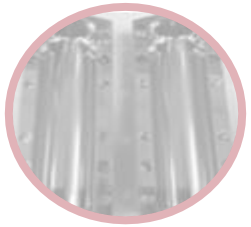


Fabrication

Characterization at 4 K

Axions

Axions are a promising dark matter candidate

Axion predicted mass can vary of many orders of magnitude: our range of interest is $10^{-6}\ eV$ to $10^{-3}\ eV$

GHz frequency range

Conversion Power

Volume

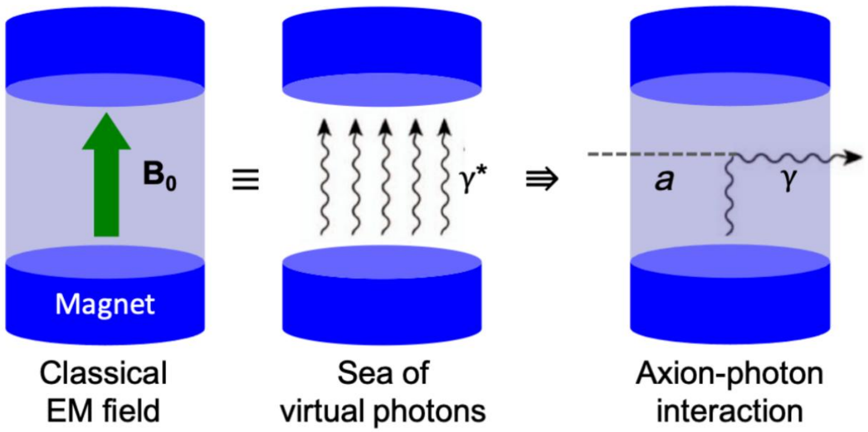
Cavity Quality Factor

$$P_{a\gamma\rightarrow\gamma} = k \cdot B^2 \omega_0 V \frac{Q_a Q_c}{Q_a + Q_c}$$

Magnetic Field

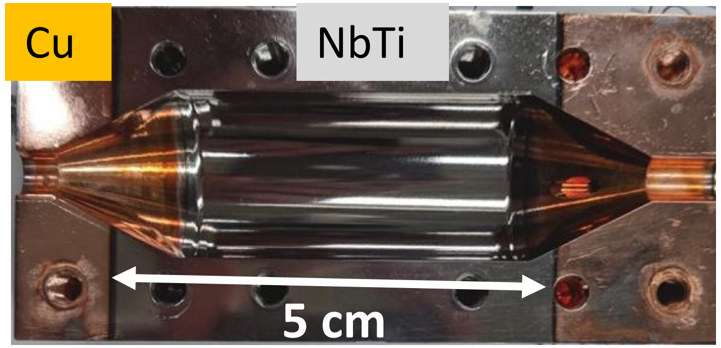
Axion Quality Factor (10^6)

How to detect them?



Y. K. Semertzidis e S. Youn, *Science Advances*, vol. 8, fasc. 8, feb. 2022

Axion → Photon



$\omega = 9GHz$

D. Kim *et al.* JCAP03(2020)066

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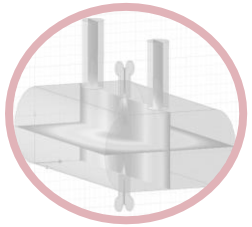

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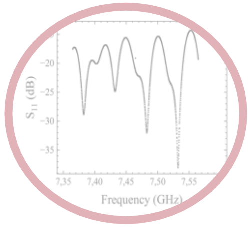

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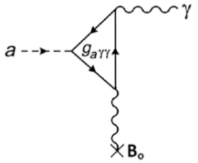

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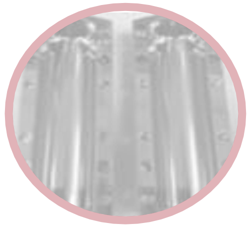

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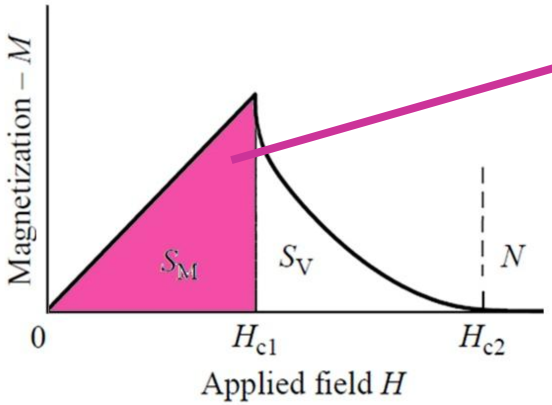
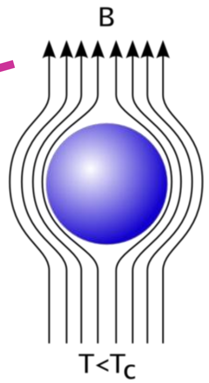
MATERIAL CHOICE

Accelerators Cavities – RF

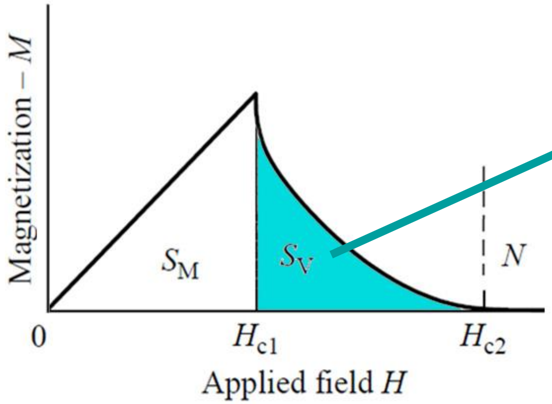


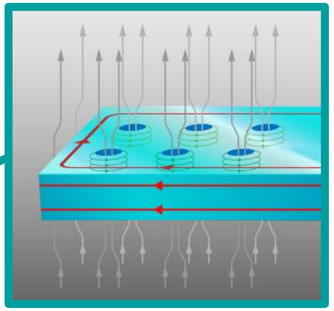


Complete
Flux Expulsion

Meissner state – no magnetic field

Magnets – DC





Mixed state – flux vortex formation

Vortexes are pinned by defects
Flux PINNING

RF + static magnetic field
is a quite new regime for superconductive devices

MATERIAL CHOICE

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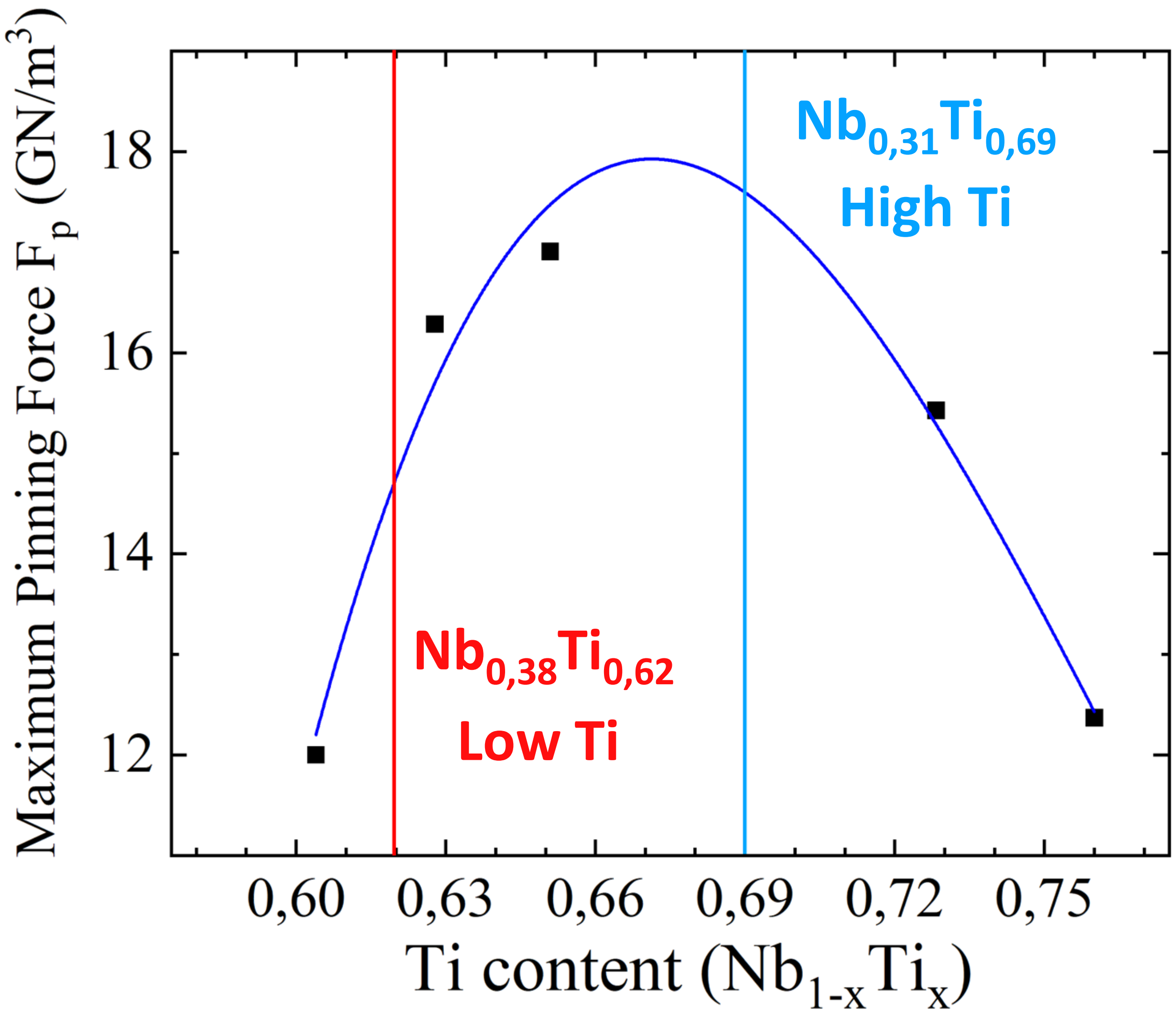
UNIVERSITÀ DEGLI STUDI DI PADOVA

Material	Tc	Bc2	Note
Nb	9.2 K	**0.4 T**	**Not suitable at high Magnetic field**
NbTi	~ 9.5 K	**~ 14 T**	**Simple preparation**
MgB_2	~ 32 K	**~ 15 T**	**Preparation is a challenge**
Nb_3Sn	~ 18.3 K	**~ 30 T**	**Preparation is a challenge**
REBCO	~ 93 K	**~ 100 T**	**Available in tapes**

NbTi was the obvious choice (although not the best performing) to build and test a SC haloscope **for the first time**

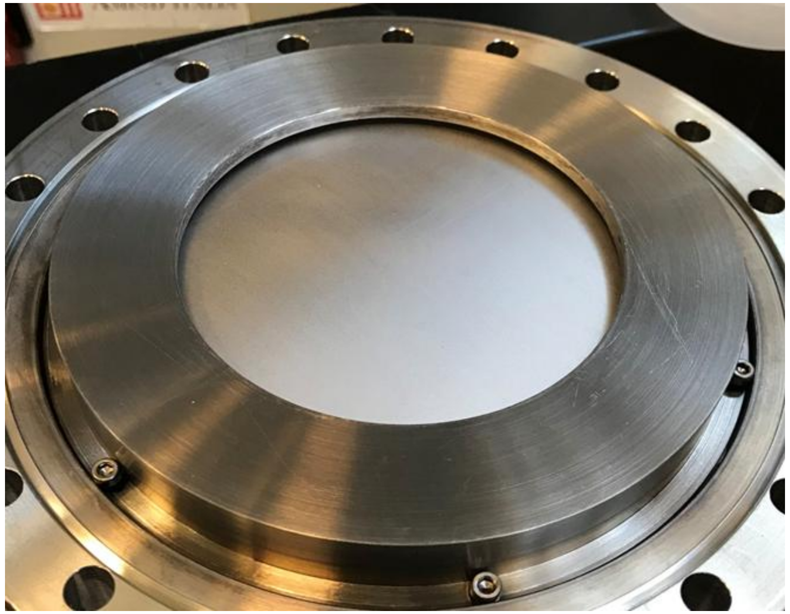
Material Choice



J. C. McKinnell, P. J. Lee, and D. C. Larbalestier,
IEEE Transactions on Magnetics, vol. 25, no. 2, Mar. 1989

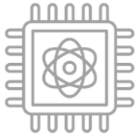
Higher Ti content gives higher pinning force $F_p \propto \dfrac{1}{dissipation}$ up to a maximum

Material Choice



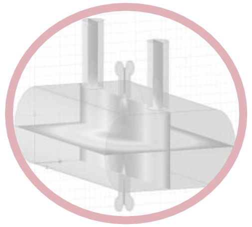
$Nb_{0.38}Ti_{0.62}$
1 mm sheet

$Nb_{0.31}Ti_{0.69}$
5 mm bulk



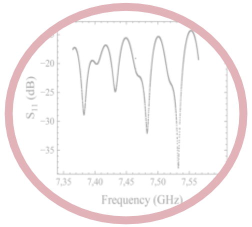
Quantum computing

Aluminum cavities for 3D transmon architecture



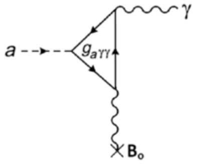
Design of a 7.46 GHz cavity

Fabrication using
pure Al vs Al alloy



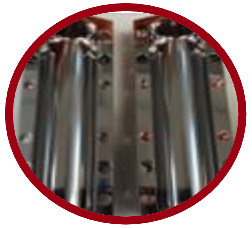
Characterization of the
Cavity + Qubit

Axion search



NbTi thin film on Cu cavities as haloscopes

Material selection & Characterization

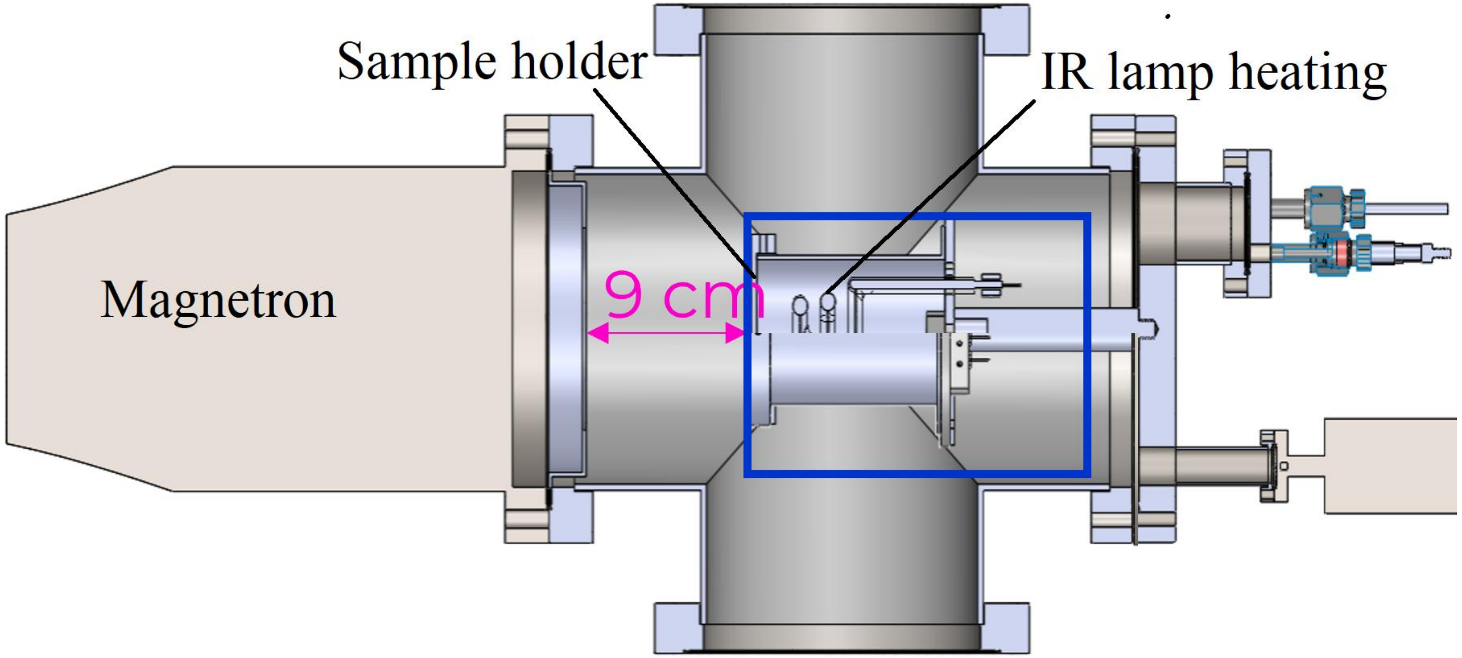


Fabrication

Characterization at 4 K

FABRICATION

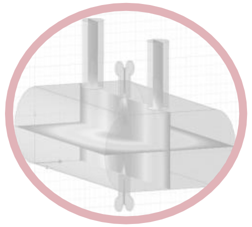
DC Magnetron Sputtering



- Single NbTi target
- Ar pressure $6 \cdot 10^{-3}$ mbar
- T substrate 500 °C
- Film thickness 2.5 – 3.5 µm
- No bias voltage

Quantum computing

Aluminum cavities for 3D transmon architecture



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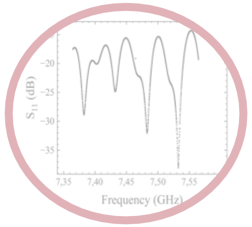
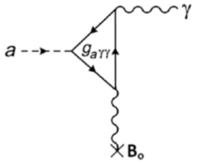


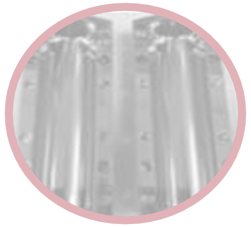
Characterization of the Cavity + Qubit

Axion search



NbTi thin film on Cu cavities as haloscopes

Material selection & Characterization

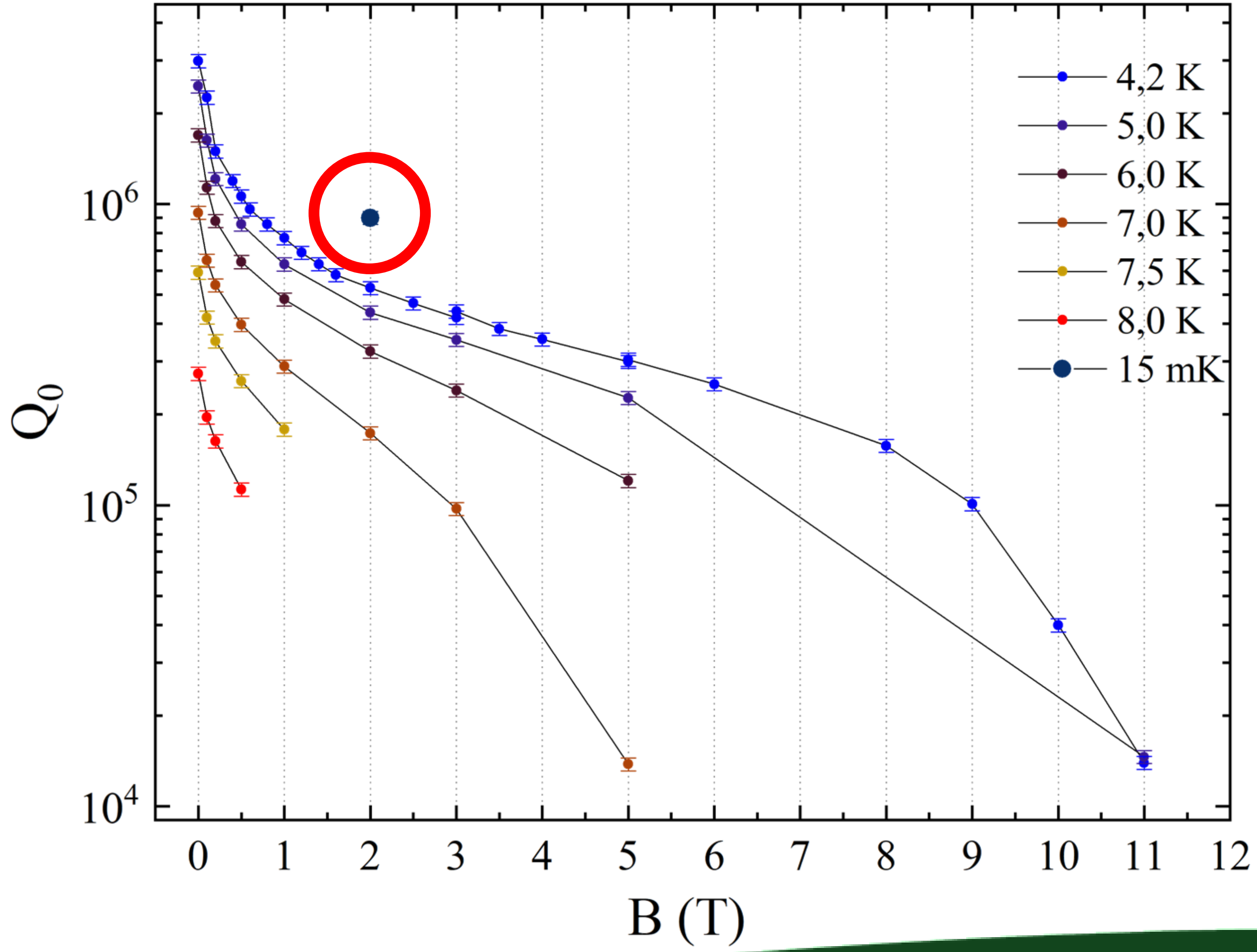


Fabrication

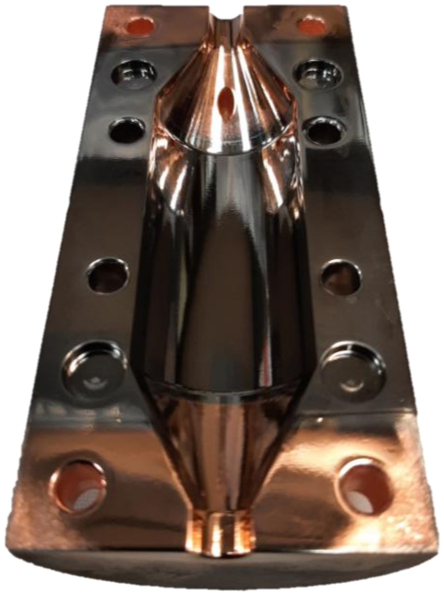
Characterization at 4 K

CAVITY CHARACTERIZATION

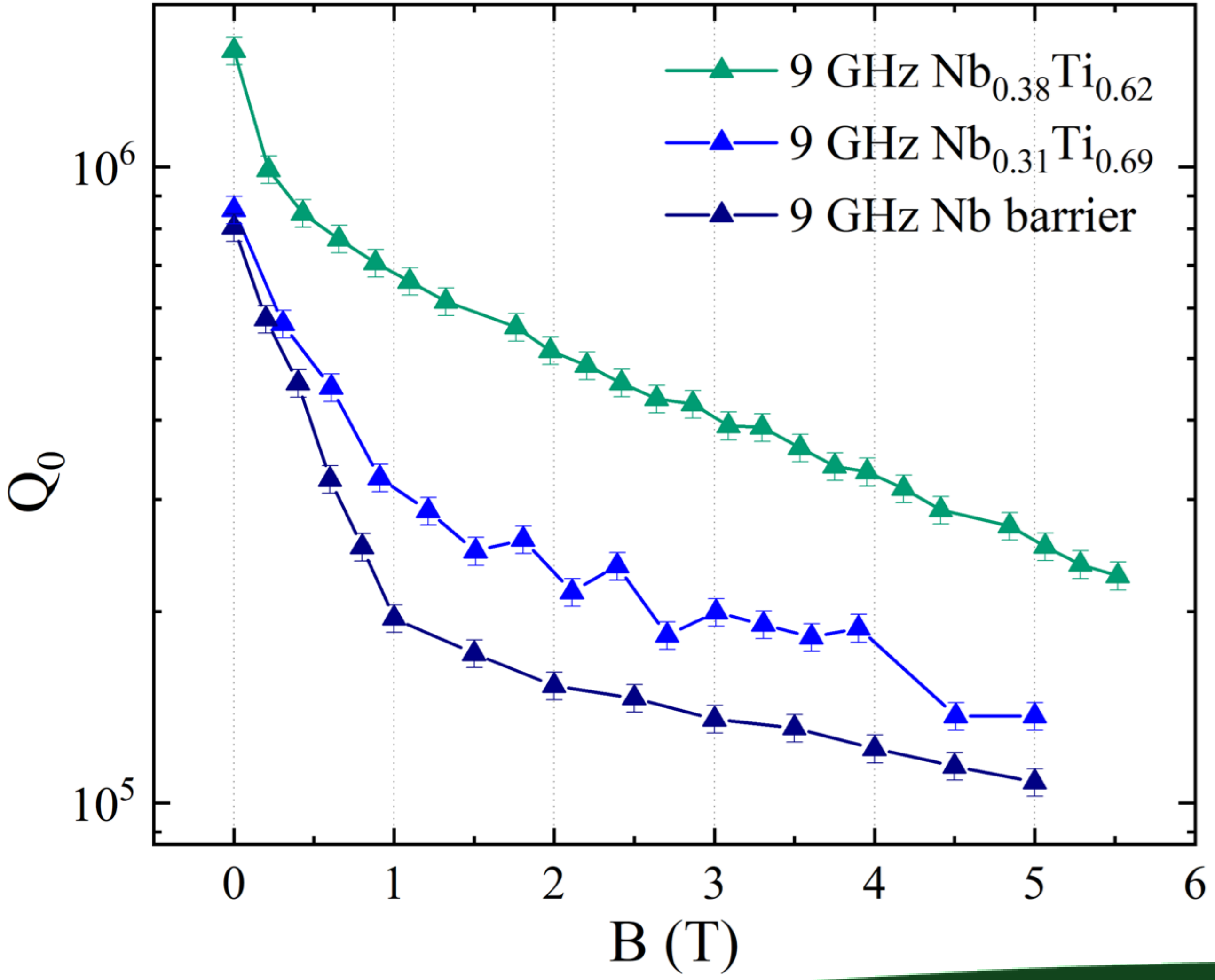
7 GHz



Cavity Characterization



9 GHz



All measures at 4 K

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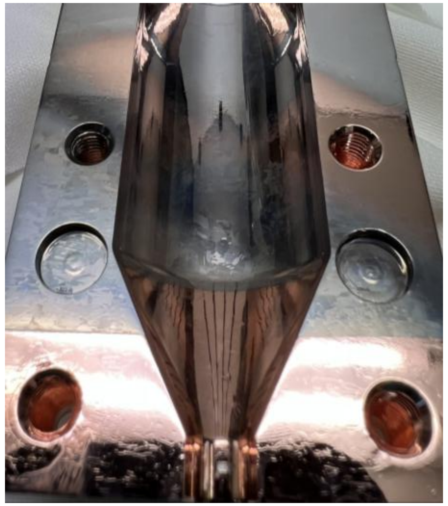
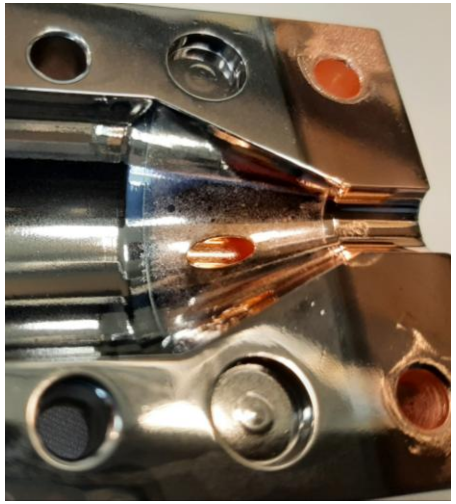
All measures at 4 K

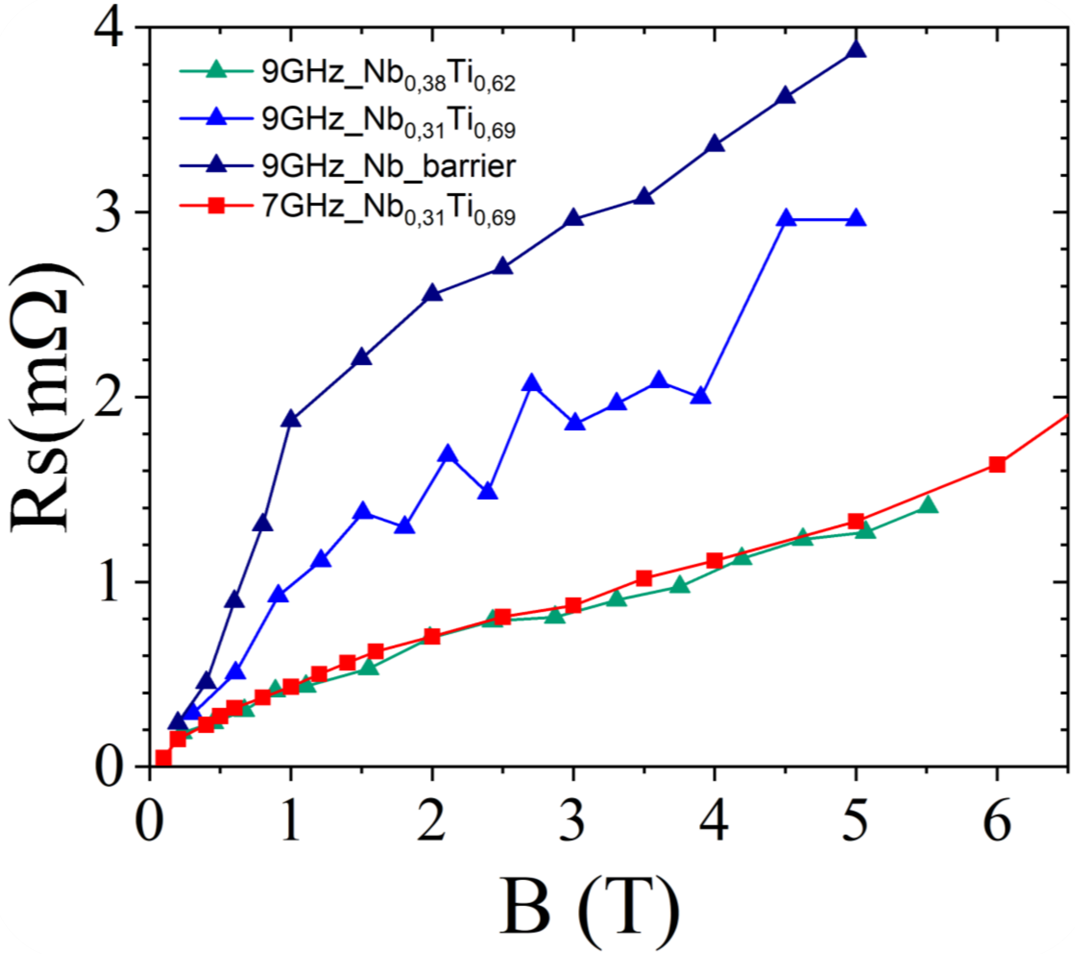
Defects on the cavity surface

Due to multiple surface treatments





Pitting + NbTi coating on Cu cones



Conclusions

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Quantum computing

- Pure Al cavity with non-optimized surface showed $\boldsymbol{Q_L} = (\mathbf{2.2} \pm \mathbf{1.0}) \cdot \mathbf{10^5}$
- The Qubit was successfully characterized but needs fabrication optimization

Axion search

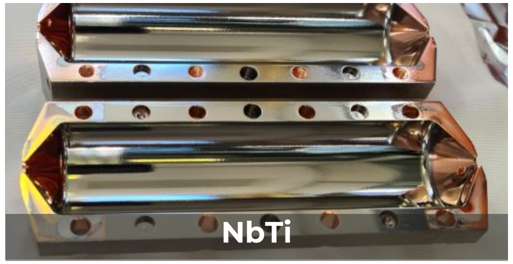
- Four NbTi on Cu cavities fabricated
- Good performance obtained compared to state-of-the-art

Giovanni Marconato, *Quantum Technologies for Fundamental Physics Workshop, Erice, Italy, Sept 2023*

NbTi

7 GHz

$\mathbf{9 \cdot 10^5}$

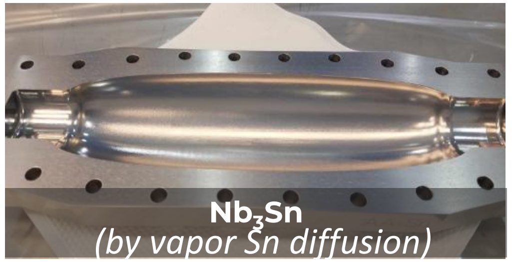


Sam Posen, *Quantum Technologies for Fundamental Physics Workshop, Erice, Italy, Sept 2023*

Nb_3Sn

3.9 GHz

$\mathbf{1 \cdot 10^6}$



Woohyun Chung, *Quantum Technologies for Fundamental Physics Workshop, Erice, Italy, Sept 2023*

REBCO

5.4 Gz

$\mathbf{1.5 \cdot 10^7}$

All @2T and 4K

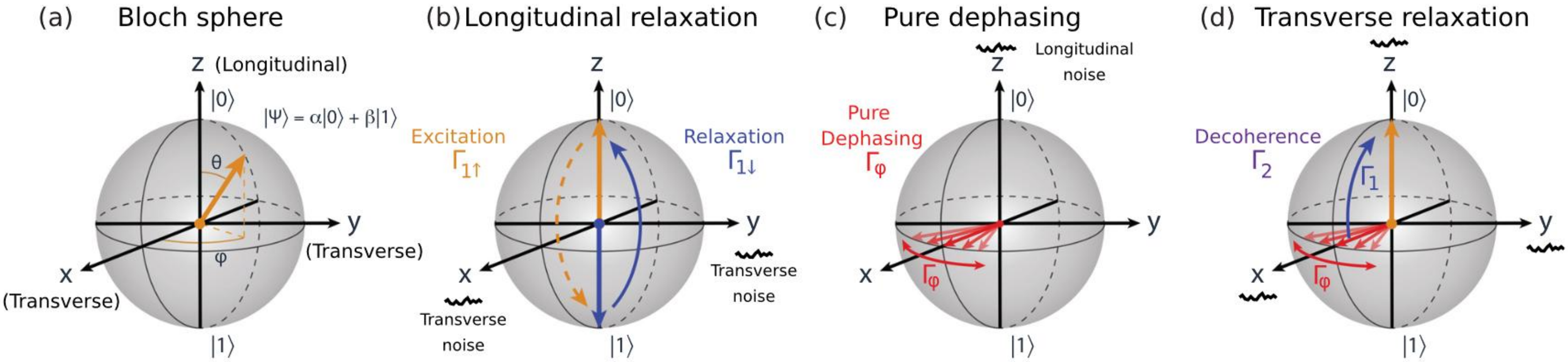
THANK YOU

FOR YOUR ATTENTION

Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

BACKUP



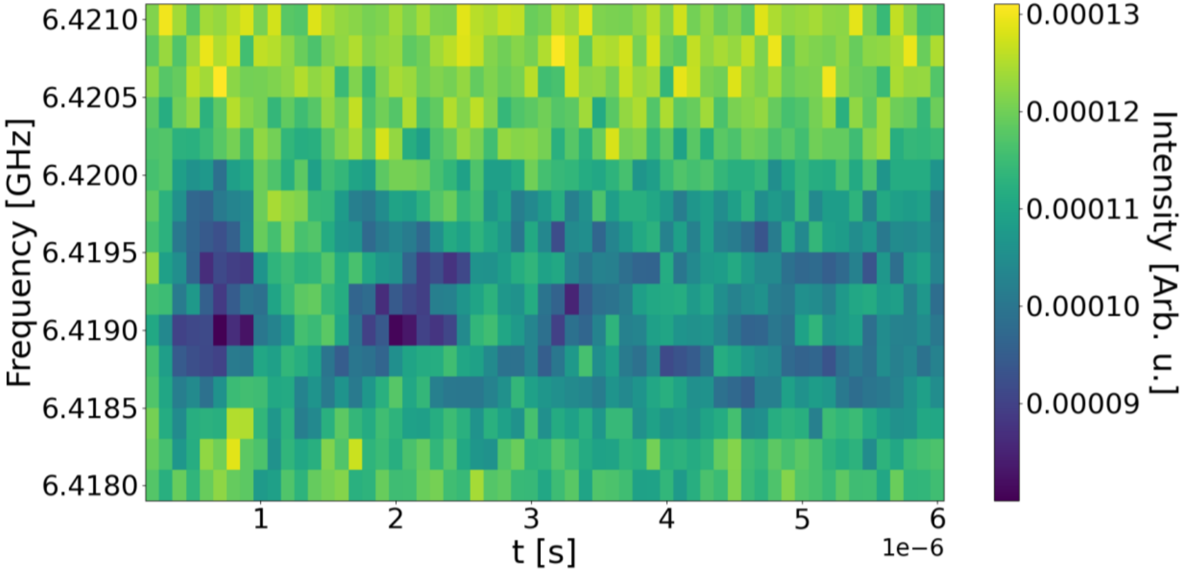
P. Krantz, et al., *Applied Physics Reviews*, vol. 6, fasc. 2, giu. 2019

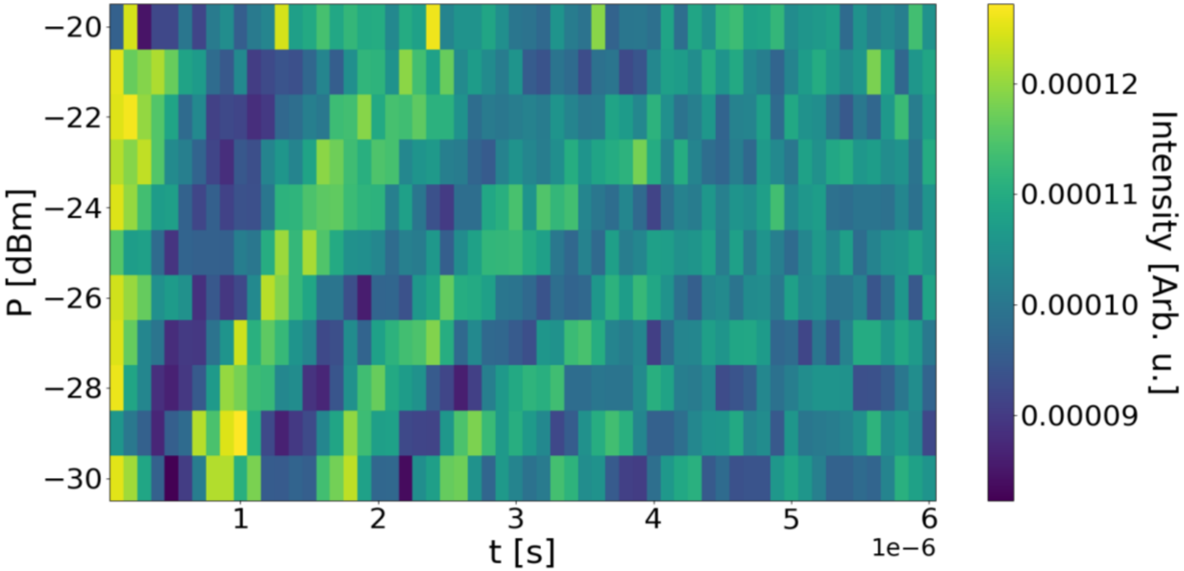
$$T_1 = \frac{1}{\Gamma_1}$$

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\varphi}$$

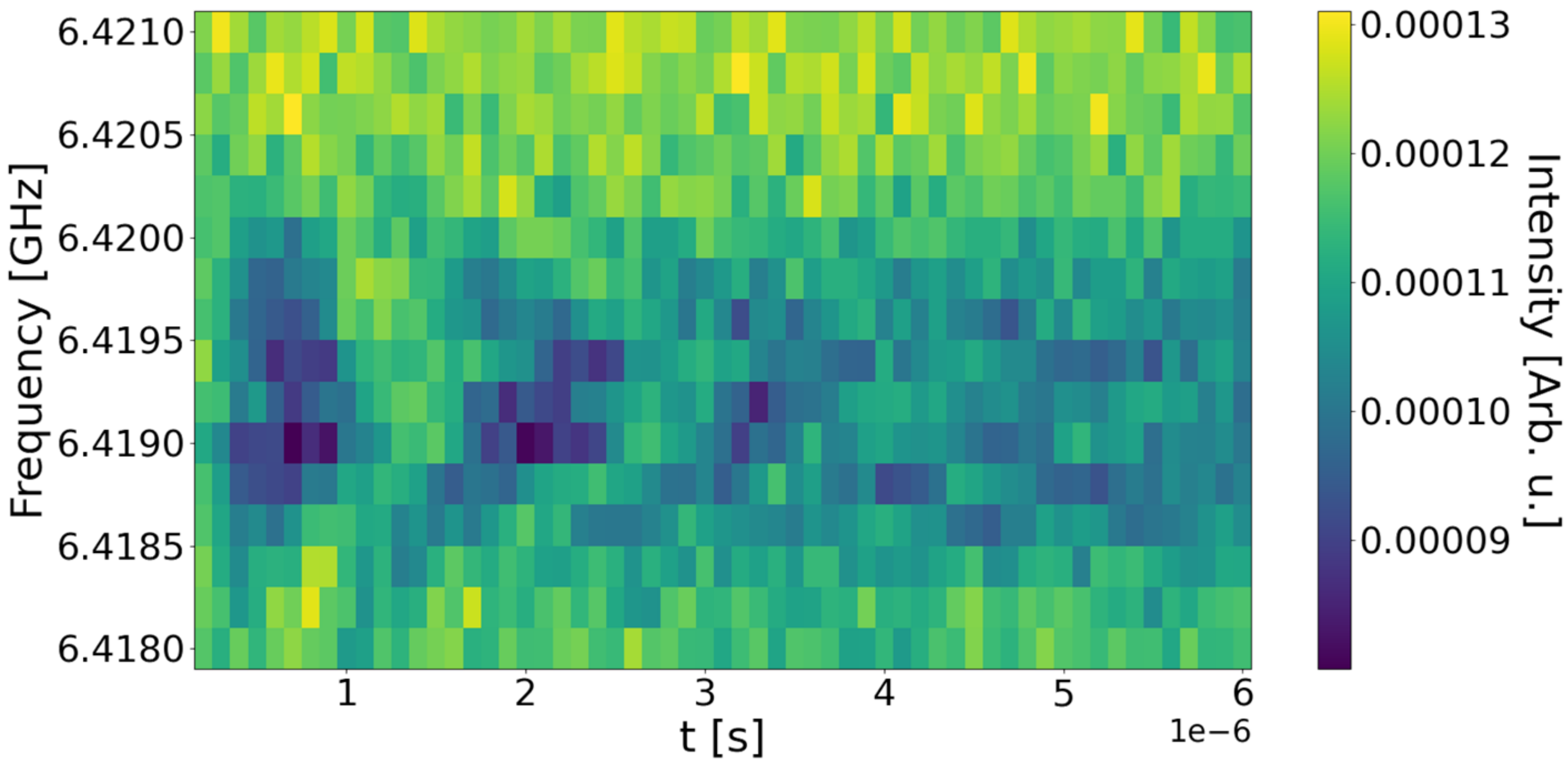
Backup

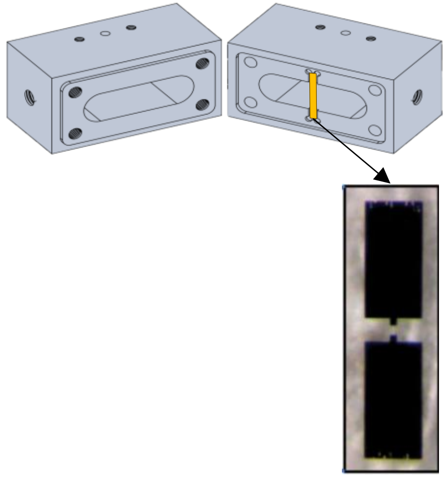
$$p \propto \cos^2\left(\pi\tilde{\Omega}_R t + \phi\right)e^{-\frac{t}{T_1}} \qquad \tilde{\Omega}_R = \sqrt{\Omega^2 + \Delta^2} \qquad \Omega = \frac{d \cdot E}{\hbar}$$



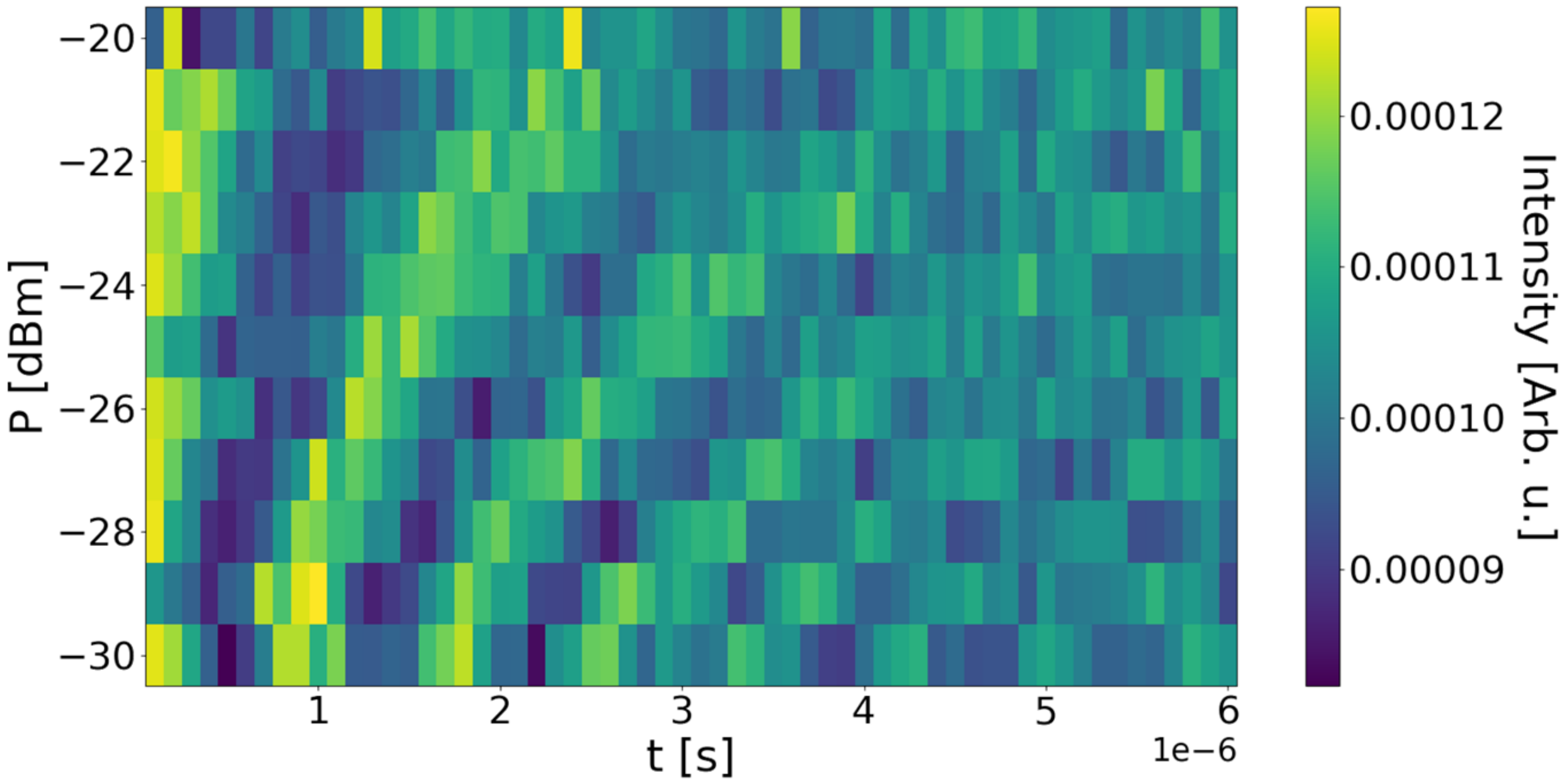


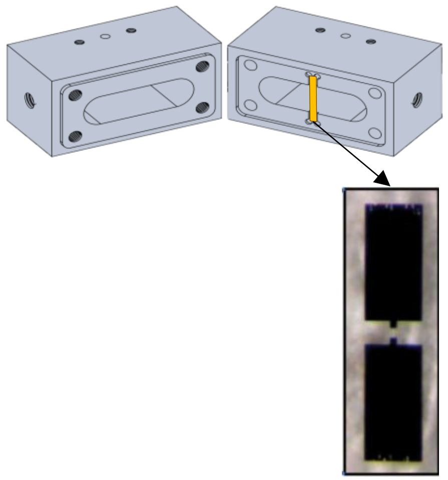
Chevron plot



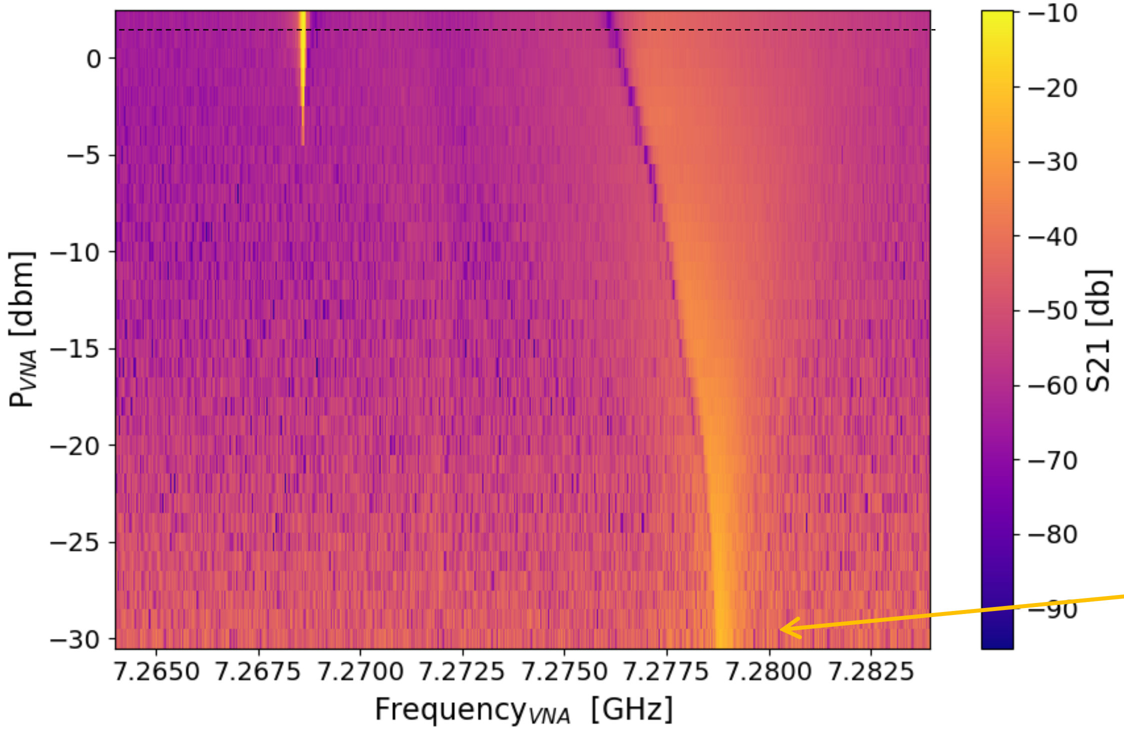


Power scan plot



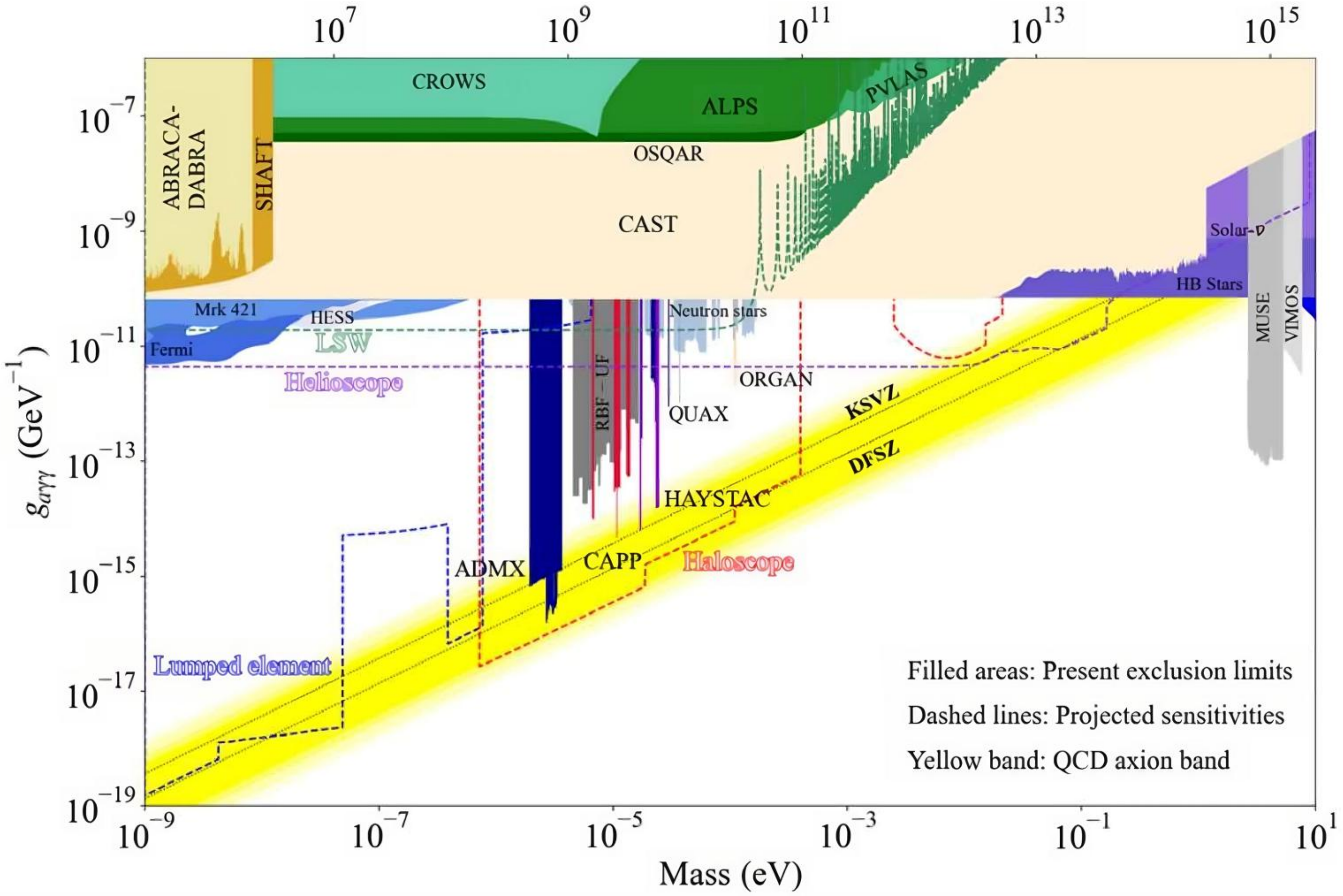


Bare cavity = 7.268 GHz



Coupled system with qubit in 0

Backup



Semertzidis and Youn, *Sci. Adv.* **8**, eabm9928 (2022)

Conversion Power

Coupling Constant — Dark Matter Axion Density — Volume — Cavity Quality Factor

$$P_{a\gamma\to\gamma} = g^2_{a\gamma\gamma}\frac{\rho_a}{m_a}B^2\omega_0 V C\frac{Q_aQ_c}{Q_a+Q_c}$$

Axion Mass — Magnetic Field — Resonant Frequency — Axion Quality Factor (10^6)

D. Kim *et al*. JCAP03(2020)066

Scan Rate

Magnetic Field — Volume — Cavity Quality Factor

$$\frac{df}{dt} \propto \frac{B^4V^2C^2}{K_B^2T_{sys}^2}Q_aQ_c\frac{1}{1+Q_a/Q_c}$$

System Noise — Axion Quality Factor (10^6)

Fluxon Dissipation

Fluxon viscosity

$$\eta = \frac{\phi_o B_{c2}}{\rho_n}$$

Pinning force

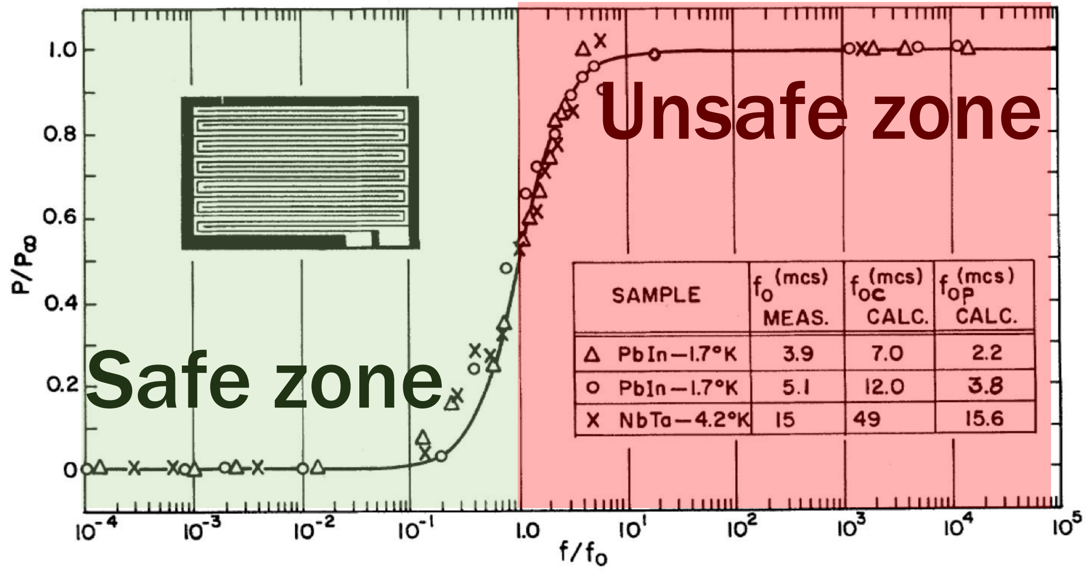
$$k = \frac{2\pi J_c \phi_0}{d}$$

$$m\ddot{x} + \eta\dot{x} + kx = J_{rf}\phi_O$$

$$\omega_o = \frac{k}{\eta}$$

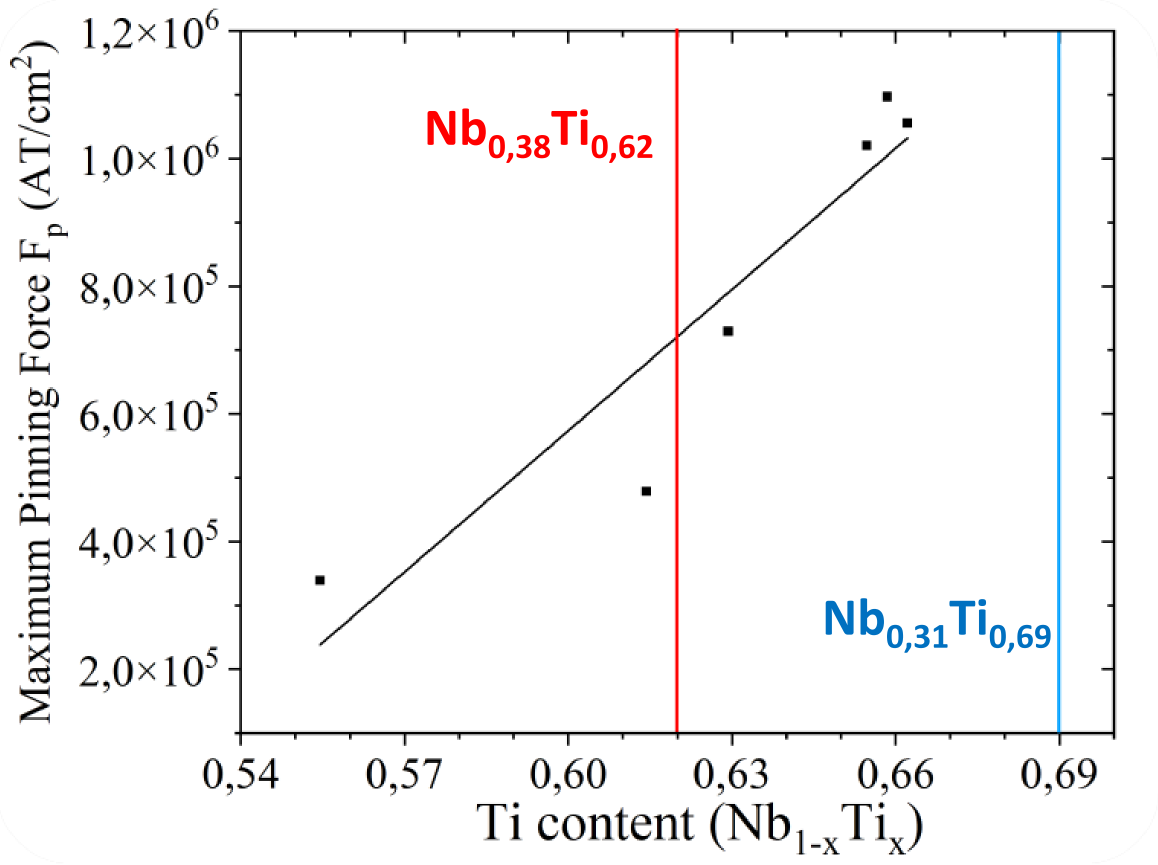
$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n\sqrt{B_o}J_c(B_o)}{\sqrt{\varphi_o}B_{c2}}$$

Depinning frequency



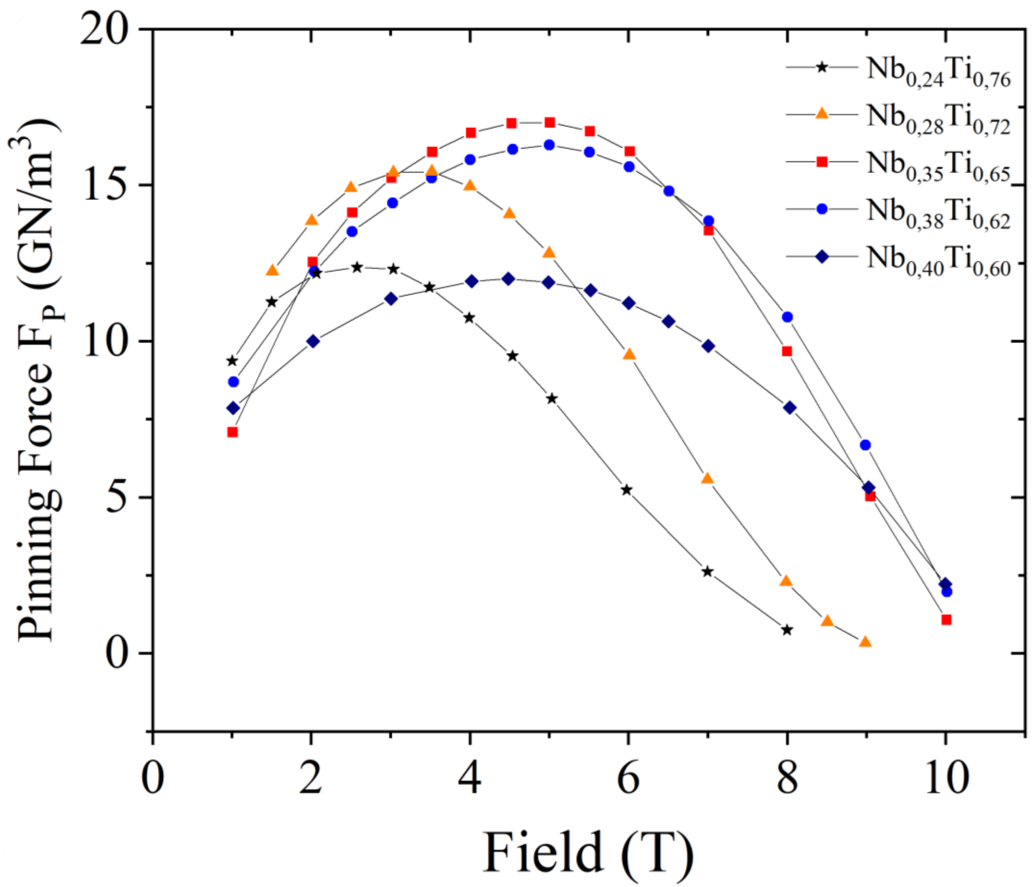
BACKUP

NbTi pinning force dependency on Ti content

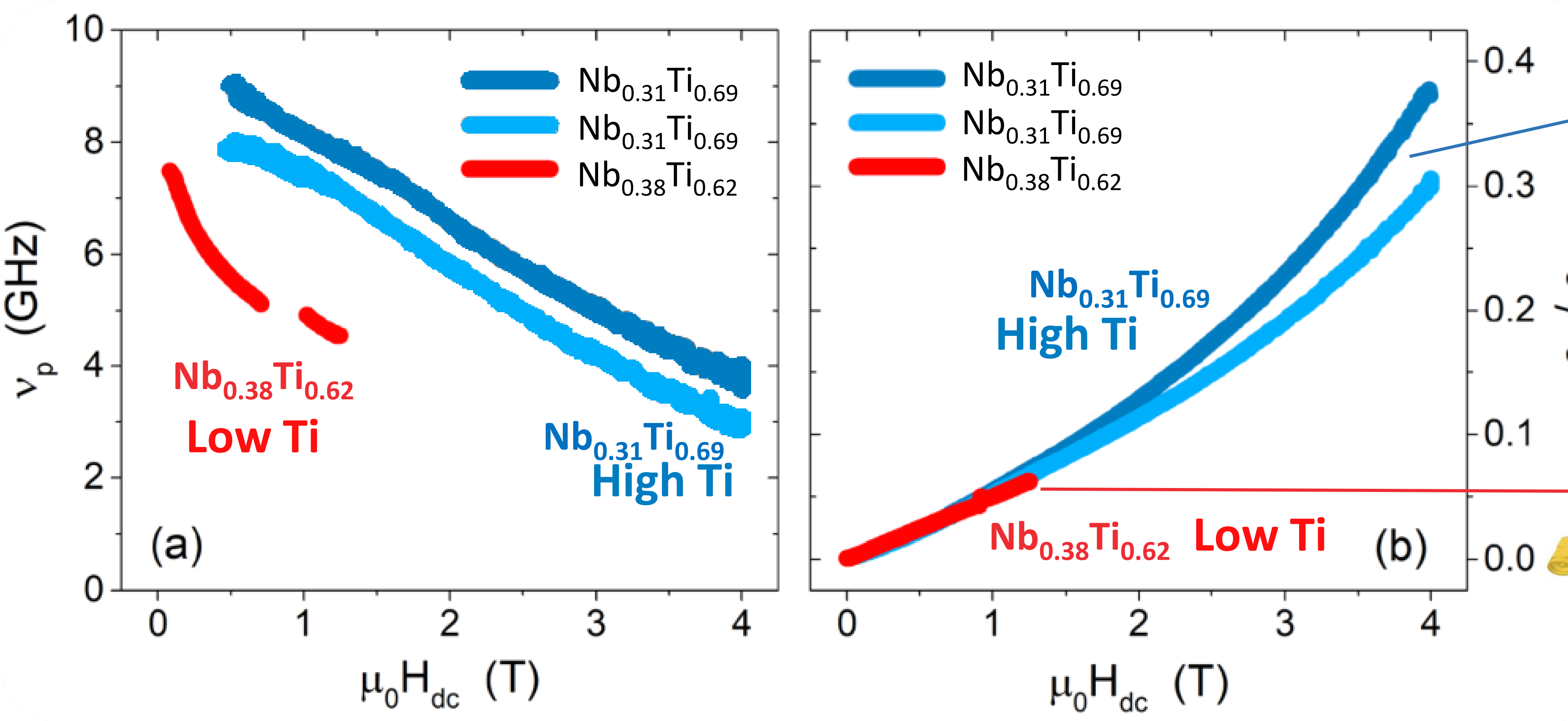


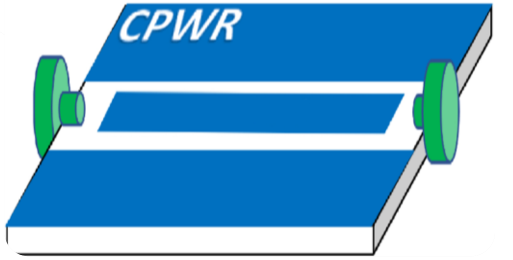
H. Hillmann and K. Best,
IEEE Transactions on Magnetics, 1977

J. C. McKinnell, P. J. Lee, and D. C. Larbalestier, *IEEE Transactions on Magnetics*, 1989



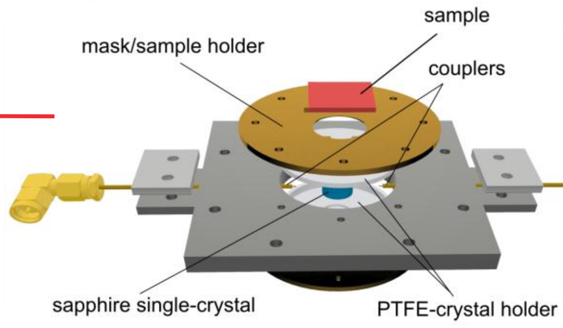
BACKUP





G. Ghigo *et al.*, *Materials*, 2022

Done at INFN Torino



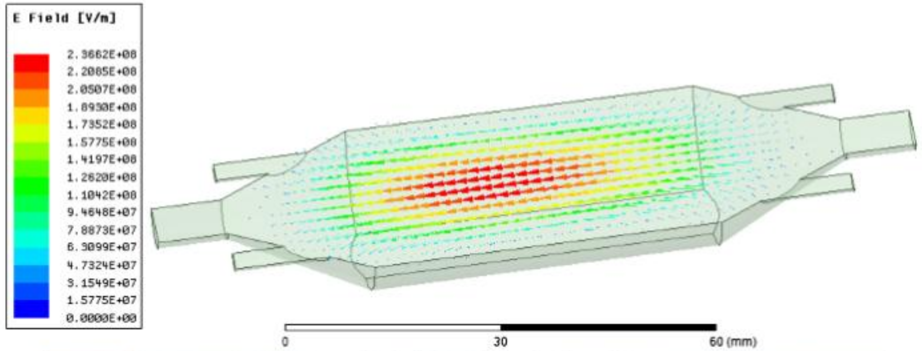
A. Alimenti *et al.*, *Sensors*, 2023

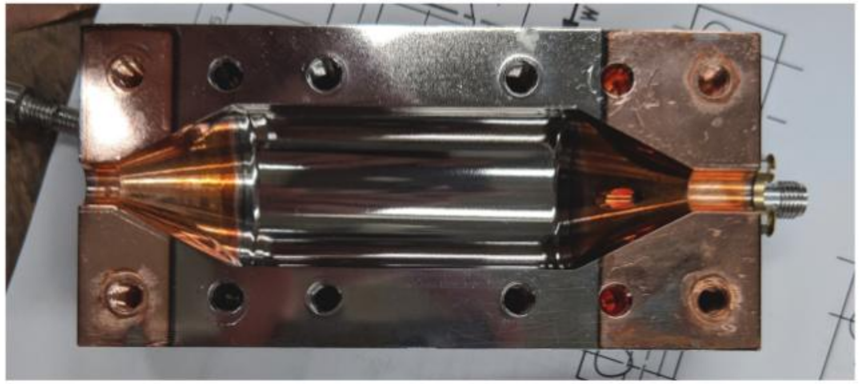
Done at Roma 3 university

$Nb_{0.31}Ti_{0.69}$ is better or similar at most

BACKUP

Hybrid structure advantages





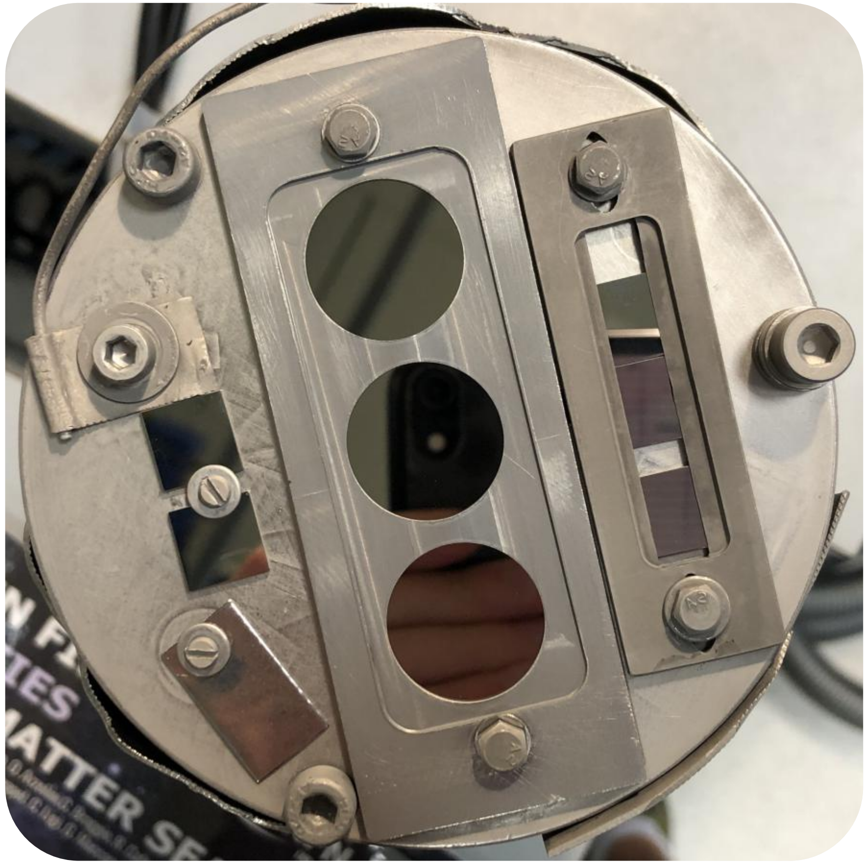
Using copper ends the quality factor is limited

$$Q_0^{max} \simeq 1{,}3 \cdot 10^6$$

But less dissipation due to fluxon movement!

Backup

- Nb_3Sn by DC Magnetron Sputtering for high Magnetic field applications



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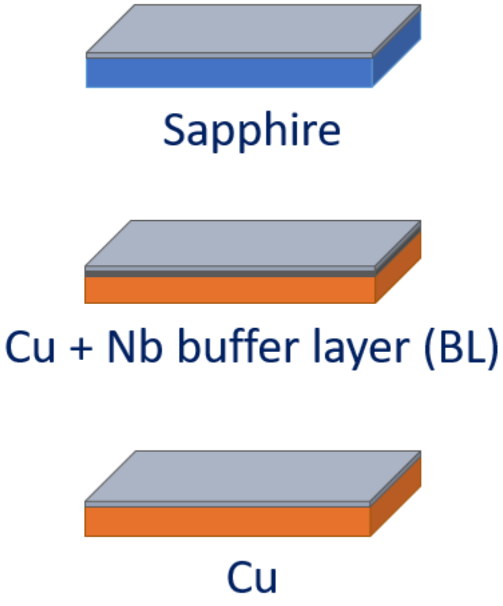

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